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ABSTRACT

This course was designed to provide the water resource technician or manager with information which will aid in the implementation of improvements of present land use practices and to illustrate alternative concepts and techniques in land and water use for increasing and improving the multiple products of watershed lands. (Author/CO)

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Resource Development of Watershed Lands

A Six Week Short Course

U S DEPARTMENT OF HEALTH,
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FOREWORD

This course has been developed for medium level technicians and professionals engaged in the management and development of watershed lands in developing nations. A major aim of this syllabus is to provide the water resource technician or manager with information which will aid him in the implementation of improvements of present land use practices and to inform him of alternative concepts and techniques in land and water use that might be applied to increasing and improving the multiple products of the watershed lands of his or her country.

It should be understood that because of the large scope of this syllabus, exact solutions to each specific problem of watershed lands as they may exist under the physical, social and economic conditions in each of the developing nations cannot be given.

Watershed lands are defined broadly as habitable areas of the earth, but which do not include well defined agricultural lands, urban areas, or special reserve areas. Because the production from these lands is inextricably linked with water, a basic portion of the course will deal with fundamentals of hydrology; and, because most of the problems in developing the multiple products of watershed lands are of social and economic origin, the course will emphasize this aspect of development.

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Development and Management of Watershed Lands

Introduction

Beyond the limits of well-defined agricultural lands and urban areas lies a major portion of the earth's habitable land surface, a residual often classed as forest or rangeland, wild lands, marginal lands or simply undeveloped lands. For lack of a more specific generic term, these residual lands will be termed watershed lands. They include more than 80 percent of the 25 billion acres of land on earth. It is to these watershed lands that we must look for increased productivity of food, fiber, energy, and living space for our burgeoning population, and it is these lands that currently stand in great jeopardy all over the world.

This course is directed toward the understanding, planning, development, and management of the land and water resources of watershed lands. It is aimed particularly at some of the major problems that concern the use of these lands in the developing countries.

Problems of Watershed Lands

The problems of watershed lands in the developing countries most often are deeply entwined in social and economic patterns which are incompatable with environmental limitations. At present, three billion human beings inhabit the earth. Each day, 200,000 more individuals are added to our planet's population. By the year 2000, which is only 21 years away, these 3 billion may have increased to 6 billion. As the growing population places increasing pressures upon global resources, our fragile planet will need increasingly careful management if the survival of mankind is to be assured. However, human survival alone is not now and has never been an acceptable goal for any nation; this is true today more than ever before. The world's developed nations have become accustomed to increasingly high living standards based upon the consumption of a far greater than proportionate share of the world's resources. The developing nations are aspiring to equal economic and social standards that would require a more equitable share of these resources. It is these aspirations, in the face of ever increasing doubts about our planet's capability to even feed its population, that place mankind in a most vulnerable world situation.

Worldwide, the ratio of land to population is dwindling: in a number of countries, the amount of cultivated land per person is less than a single acre. Only a few decades ago, food production could be increased in most countries by bringing additional acres under cultivation or by extending grazing areas; now that option is disappearing in many regions.

At present, between 50 and 80 percent of the population of the developing nations live on watershed lands. For these millions of people it is a fact of life that the harder they work, the poorer they get. Their land is either too steep or too dry or the soil is too poor to support more than a mean level of existence for a few people. Because of increasing population and intractable patterns of intensive land use and tenure, fragile environments are being subjected to mistreatment which they cannot much longer sustain.

As populations increase the only alternative is for rural peoples to migrate into increasingly fragile areas. In the more humid regions, forested slopes are cleared for fuel, fodder and primitive cultivation. Fires are allowed to escape from fields and burn indiscriminately; forests are being grazed to an extent that prevents their reproduction; networks of trails are established with no concern for the erosion hazard they create. The consequences are accelerated soil loss and land deterioration, environmental degradation and further impoverishment of the rural inhabitants themselves. In more arid areas where cultivation or wood harvesting is not possible, overgrazing is practiced to the extent that more than 1.5 million square miles of the earth have been converted to unproductive deserts during the past fifty years.

Of at least equal importance to the loss of the productivity of watershed lands, in both humid and arid areas, is the loss of the protective cover of the soil and the subsequent reduction of the soil reservoir — the principal means by which water and erosion are controlled on watershed lands. The results have been increased flooding of valleys and the shifting of stream beds accompanied by damage from water and silt to prime agricultural land, irrigation structures, reservoirs, settlements, and communications. Stream flow during dry periods becomes unreliable and insufficient for the dilution of disease carrying pollutants, the maintenance of irrigation works, and for urban and industrial needs. Ground water levels decline, resulting in the failure of springs and wells.

Examples of Watershed Lands and Their Problems

Steep and Mountainous Watershed Lands

Steep and mountainous watershed lands make up nearly one quarter of the earth's land surface, and are occupied by 10 percent of the total world's population. A great proportion of these lands have mesic or humid climates, vegetative cover (often forest) with little arable soil and low population densities. Some of the most severe problems of steep land watersheds are seen in Nepal where erosion, accelerated by man's activities, is contributing 250 million cubic meters of silt to the Ganetic Plain each year. According to Napli observers, the beds of the rivers in the Terai Plain of southern Nepal are rising by 15 to 30 centimeters annually which leads to flooding and shifts in river courses. The Kosi River, for example, has shifted its course 115 kilometers westward within the past 150 years, leaving 15,000 square kilometers of once fertile land buried under a mass of sand and rubble. This process has displaced 6.5 million persons.

The ever increasing populations of Nepal and other countries in the region are pushing ever further into the mountains and higher up the slopes in order to seek a means of livelihood. Even with the aid of terracing, which the farmers of Nepal have been practicing for centuries, these slopes are too steep and the soils too thin for intense cultivation. Nevertheless, a single acre of cultivated land must now support four people. The demands of increasing population result in less suitable soils and steeper lands being brought into cultivation, leading to a reduction of overall productivity in the country. In the densely populated eastern hills of Nepal, as much as 40 percent of what once was farm land has been abandoned and allowed to revert to bush because it is no longer fertile enough to support crops. These lands are severely eroding and are the sites and sources of massive land slides and severe gully erosion. However, cultivation is responsible only in part for the rapid deterioration of the watersheds. Nepal's forest lands stand in much greater jeopardy. The demands made by increasing numbers of livestock (over 15 million at present) are taking their toll on the forests of the steep hillslopes by fodder harvesting and overgrazing. Forest and range fires also present a serious problem.

The annual per capita energy consumption in Nepal is small compared to that of developed countries (e.g., only 2.5 Geal as compared with 30 Geal for Switzerland). Nevertheless, 6.6 million cubic meters of wood are consumed annually. In some regions of the country it is estimated that 90 percent or more of wood extraction from the forests is for fuel purposes.

In many of the steep and mountainous watershed lands of the world, the effects of timber and firewood extraction, forest clearance for cultivation, grazing, looping for fodder and burning of the undergrowth, combined with inefficient timber utilization are causing a general degradation of the forests by thinning, overaging and finally destruction. It is evident that the destruction of the forests of these steep and mountainous watersheds is progressing every year. In Nepal, for example, these lands (over 80 percent of the country) are likely to be all but totally denuded by the end of the century.

This calamity has already taken place over much of the East African highlands. In Ethiopia, erosion from the mountain studded 6,000 foot high Amhara Plateau produced the silt carried by the Nile that fertilized the agricultural flood plain of Egypt for centuries. Now, the high dam at Aswan traps the silt and helps control the Nile's floods. The dam has created a lake of over 5,000 square kilometers which extends from Aswan to the border of Somalia, and which receives an estimated 90 million tons of sediment each year, giving the lake a life expectancy of only 500 years in a land a cultural history of more than 5,000 years. The rate of sedimentation may increase in the future. At one time 75 percent of Ethiopia was covered with forests which moderated the process of soil loss. However, recent surveys indicate that substantial forest cover has diminished to only 4 percent of that nation's total land area. Deforestation is still proceeding at an estimated rate of 1,000 square kilometers per year.

In great portions of the Andes mountain range of South America, deforestation is almost complete, particularly in Peru. In Peru's mountainous region, which covers more than 1/3 of the country, the population has doubled and redoubled in this century. The mountain farmers have been forced into large scale deforestation, overgrazing, overcropping, and drastic crop reduction during the fallow periods of shifting agriculture. In some areas the hill people have been driven to digging up even the roots of trees and shrubs to burn for fertilizer, thereby greatly increasing the already depleted soil's susceptibility to severe erosion. As in the Andes, devegetation of steep and mountainous watershed lands is also being accelerated in Eastern India, Pakistan, Thailand, the Philippines, Indonesia, Malaysia, Nigeria, Tanzania, and many other countries.

Dry Watershed Lands

Arid and semi-arid regions are not often thought of as watershed lands. However, the water relationships of these regions are perhaps more critical to a greater number of people on earth than those of more humid regions. Water is always in critical balance with arid ecosystems and this balance is presently being upset by man and his animals at alarming rates over vast acreages of the earth.

Dry regions cover more than one-third of the earth's land surface, and slightly over half of their area is inhabited by 630 million people. The remainder is climatically so arid and unproductive that it cannot support human life. But the degradation of land and water resources by human activities is turning potentially productive dry lands into unproductive deserts in Asia, Africa and Latin America. This process is calld desertification. It has been estimated that a collective area larger than Brazil, with rainfall above the level classified as semi-arid, has been degraded to desert-like conditions. This does not take into account the far greater degradation that is taking place within the potentially productive semi-arid zones.

About 60 million people in the developing countries live on the semi-arid interface between deserts and more humid areas. Desert encroachment in West Africa has received the greatest international attention recently. Although some reports from the Sahara seem wildly overdrawn, reliable estimates indicate that 250,000 square miles (650,000 square kilometers) of land suitable for agriculture or intensive grazing have been forfeited to that desert over the past 50 years along its southern edge.

One of the most outstanding examples of the problems of dry watershed lands is typified by the arid lands of India which include the sandy wastes of the Thor Desert of Western Rajasthan, a larger inhabited but desolate area surrounding it that is often called the Rajasthan Desert, and other dry areas further south and east. An average of 61 people now occupy each square kilometer of these lands. The practical consequence of the pressure this population exerts has been the extension of cropping to submarginal lands which are fit only for forest or range, helping make this perhaps the world's dustiest area. Meanwhile, as the land available for forage shrinks, the number of grazing animals swells. The area available exclusively for grazing in Western Rajasthan dropped from 13 to 11 million hectares between 1951 and 1961, while the population of goats, sheep and cattle jumped from 9.4 to 14.4 million. The livestock population is still growing. During the decade of the 1960's the cropped area expanded from 26 percent to 38 percent of the total area, squeezing the grazing area even more.

As long as current land use patterns continue, the livelihood of tens of millions living in the arid lands of India will, at best, remain at its current dismal level. At worst, and most probably, a prolonged drought in the future will mercilessly rebalance the number of people with the available resources. As it is, relief programs for the arid zones are seriously draining the governments' funds and food stores.

Present land use patterns in desert environments must be reshaped in order that delicate water relations are not pushed beyond their limits. As the number of people and animals living in the arid zones climbs and the quality of the land on which they must live simultaneously declines, the impact will be global unless solutions are implemented.

Humid Tropical Watershed Lands

There is a common fallacy that however much steep and mountainous lands might loose their production potential by erosion or how much marginal land is degraded into desert, the world can fall back on its tropical watershed basin lands. One quarter of the Asian, African and Latin American tropics are occupied by these lands. The Amazon Basin, for example, includes nearly 3 million square miles, 40 percent of the South American continent, yet it is inhabited by less than 3 percent of its population.

Another common fallacy is that these lands, because they support a rich and diverse plant cover, must also be highly suited to intensive agriculture. Unfortunately, tropical rain forests are closed systems with most of the available nutrients tied up in the vegetative canopy. The nutrients are easily released to the soil if the canopy is burned. Thus, these lands are well suited to slash and burn agriculture which has been practiced in tropical regions for thousands of years. It only becomes a serious threat when production pressures become too great to allow a sufficiently long recovery period between slash and burn cycles. There is good evidence that these pressures were largely responsible for the collapse of several jungle civilizations, notably the Mayan civilization of Central America and the ancient Khmer Empire of Cambodia whose agricultural practices led to cementation and loss of fertility of the lateritic soils they farmed.

Increasing demands for food and fiber are now placing pressure upon tropical watershed lands on a global scale. In eastern Nigeria, for instance, the most densely populated part of Africa south of the Sahara, shifting agriculture has been forced into shorter and shorter rotation cycles to the point that it has become continuous cropping. The result is an almost universal progression in the loss of nutrients and breakdown of soil structure. This decline has been severe in Africa where per capita food production has actually declined over the past twenty years.

One of the best examples of the problems of tropical watershed lands are those developing in the Amazon basin. By any account, the soils of most of the Amazon basin are poor and could perhaps best be exploited through forestry or nonagricultural practices. Only about 4 percent of the Brazilian portion of the Amazon have soils with medium to high fertility. Most of the better soils are in narrow plains along the banks of rivers, and their development for large scale agriculture will require large expenditures for drainage and flood control. Nevertheless, the Amazonian governments have programs to help new farmers from other regions settle in the basin. Since 1971, fifty thousand families have settled along a proposed highway between Peru and the Atlantic. With few financial and administrative resources, and less knowledge of tropical farming techniques, even the most successful barely attain production at subsistence levels. It is probable that many more colonists will find it impossible to make a living and will abandon their plots after the soil has been severely degraded by over-intense, inappropriate cultivation.

The Watershed or a Unit for Development

The fundamental unit of water resource management is the watershed basin. It may be a catchment area for the precipitation provided to stream channels or a larger basin which contributes water to a particular river channel or set of river channels. Biologists, ecologists, and biogeographers have turned to the watershed as an ideal unit in which to develop the ecosystem approach. Systems engineers and economists view the watershed as the basis for study and development in terms of river basin planning for economic development. Hydrologists and engineers consider the watershed to be a system within which a balance can be struck between inflow and outflow of water and energy.

The term watershed implies a domain or system within boundaries. The boundaries may be physical ones, such as watershed divides, or they may be defined by processes such as runoff. The watershed domain may be further divided into subcomponents of smaller watersheds or into subprocesses such as overland flow. Watersheds may be controlled with physical structures such as the series of dams operated by the Tennessee Valley Authority in the United States or uncontrolled as are most watersheds in developing countries.

In a social science context, the watershed has emerged rather recently as a logical unit of understanding and policy making. This emergence is closely connected, in the course of general economic development, with technological change and shifting demands for the main products of a watershed: hydroelectric power; water; timber; livestock; agricultural crops and the amenities.

The Role of the Water Resource Manager

The water resource manager may be called upon to exercise control over a watershed to meet some objective through the application of upstream treatments. His objectives may be to: increase water yields; provide a dependable supply of water for downstream use; improve forest, range and small farm production on the watershed; maintain a specified standard of water qualilty; reduce erosion and flood hazard; or enhance recreation and wildlife on the watershed. These tasks might involve the selection of appropriate cover types, harvesting methods, and plant cover or crop management systems. The water resource manager may have to consider the feasibility of reservoirs in combination with upstream watershed structures and land treatments. The development of surface or ground water for human and/or animal use or small scale irrigation may also be one of his or her responsibilities. The water resource manager must be versed in hydrology and he must also be ever aware of the needs, customs and traditions of the people who live within and depend directly upon the watershed areas for their livelihoods. The lives of those people living downstream from a watershed are also affected by its multiple and integrated products. Perhaps the most important task of the water resource manager is to apply his skills toward solving, in ways which will be of greatest benefit to mankind, the numerous problems associated with land use which currently threaten large areas of the earth.

It is the task of the water resource manager to reduce this impact, but simply creating new sources of water will not solve the problem. In fact, the development of water in dry environments is often a major cause of desertification. With water, livestock numbers inevitably increase, and each new watering spot becomes a nucleus for further expanding the desert. The water resource manager in dry environments must not only know the techniques of water development, but must confront the dilemma of what is essential to the survival of society over the long term is usually at cross purposes with what is essential to the survival of the individual over the short term.

The watershed manager in humid, tropical watershed lands must be versed in small farming practices and alternatives to these practices, knowledgeable in transport systems and economic marketing, in addition to being an expert in the hydrology and soils of humid tropical regions. In steep or mountainous regions, he must be familiar with the techniques of erosion control, reforestation and forest management. He must deal with the problems of shifting cultivation, fuel wood harvesting, and forest grazing. Groundwater development and stream control may be an important part of his job.

The Development of Water Resources

There is clear evidence that the physical potential exists on earth to feed a much larger population than now lives here. Despite this encouragement, it must be remembered that the resources of individual countries vary widely. Even India, which is often cited as hopeless by professional pessimists, is capable, with its abundant sunlight and deep soils, of producing many times over the amount of food presently being grown.

Water resource development has a long gestation time before it yields benefits. Political leaders in both the rich and poor countries have short term horizons. They focus on immediate and popular concerns. Yet the conservation and production of the resources of watershed lands depend on long term and expensive commitments. Both the developed and developing countries must be ready to make this commitment to the development of the world's watershed lands if future worldwide disaster is to be avoided.

It is important to recognize that the problems of watershed lands do not necessarily arise from physical limitations nor from lack of technical knowledge. The limitations on production and abundance are found in the political and social structures of nations and the economic relations among them. The resources are there, and their successful development depends upon the will of men. The water resource manager can help strengthen this will by presenting and implementing sound, practical solutions for developing the productivity of watershed lands which will provide the greatest benefit to man over the long term.

It must be pointed out that, despite a prevailing pessimism, solutions do exist. Much is known and much more remains to be learned. The problems are complex and touch sensitive areas of the political, economic and technological structures of nations. Solutions will not be easy to find. They will require knowledge, imagination and courage, but they can be obtained when the best minds endeavor to develop wise operational policies that will also be acceptable to the public.

Quantifying the Hydrologic Cycle:
Water and Energy Budgets

The Hydrologic Balance

The hydrologic balance or water budget is both a fundamental concept of hydrology and a useful method for the study of the hydrologic cycle. The hydrologic cycle represents the processes and pathways involved in the circulation of water from land and water bodies, to the atmosphere and back again (Figure 1). The cycle is complex and dynamic but can be simplified if we categorize components into input, output or storages as illustrated in Figure 2. Input such as rainfall, snowmelt and condensation must balance with changes in storage and with outputs which include streamflow, groundwater, and evapotranspiration. The water budget is essentially an accounting procedure which quantifies and balances these components.

The quantities of water in the atmosphere, soils, groundwater, surface water and other components are constantly changing because of the dynamic nature of the hydrologic cycle. At any one point in time, however quantities of water in each component can be approximated. If we consider the total water resource on the earth, only about 3 percent is fresh water. About 77 percent of this fresh water is tied up in the polar ice caps and glaciers, and 11 percent is stored in deep groundwater aquifers, leaving 11.6 percent for active circulation. Of this 11.6 percent, only 0.55 percent exists in the atmosphere and biosphere (from the top of trees to the lowest roots). The atmosphere redistributes evaporated water by precipitation and condensation. Components of the biosphere partition this water into runoff, soil water storage, groundwater or back to the atmosphere.

The hydrologic processes of the biosphere and the effects of vegetation and soils on these processes are of particular interest to watershed managers. Processes such as interception, evaporation, transpiration, infiltration, percolation, surface-runoff, subsurface flow and groundwater flow can all be affected by land management activities. Likewise, man can alter the magnitude of various storage components including soil water, snowpacks, lakes, reservoirs and rivers. With a water budget we can examine existing watershed systems, quantify the effects of management impacts on the hydrologic cycle and in some cases predict or estimate the hydrologic consequences of proposed or future activities.

Water Budget Concept

The water budget is simply an application of the conservation of mass principle to the hydrologic cycle. That is, for a given watershed and a certain time interval:

$$I - O = \text{delta } S$$

where:

I = inflow of water to the system
O = outflow of water from the system
delta S = change in storage of the volume of water in the system.

Substituting with the hydrologic components of a watershed or river basin, the above relationship for a given time interval becomes:

$$P - (Q + ET) \pm L = \text{delta } S$$

where:

P = total precipitation
Q = total runoff or streamflow, including measured groundwater flow
ET = total evaporation and transpiration losses
L = leakage out of the system by deep seepage (–) or leakage into the system (+) from an adjacent watershed
delta S = change in storage in the system which is determined by:

$$\text{delta } S = S_t - S_{t-1}$$

where:

S_t = storage at the end of the time period

S_{t-1} = storage at the beginning of the time period

If adequate time and manpower were available, each of these terms could be either measured directly or estimated by a variety of techniques which will be discussed later. Units for water budget components are typically in areal inches or cm of water depth for the watershed being studied. By combining many processes and components together this method simplifies the analysis of the hydrologic cycle.

Water budgets can be determined for small plots, headwater drainages, large river basins or even continents. If a water budget was to be determined over one year for all land and water areas, the total change in storage would usually be negligible. The annual budget could then be approximated by using the following data from Todd (1970):

P = 9.86 x 1013 cubic meters of water falling on land surfaces
= 36.98 x 1013 cubic meters falling on the ocean
E = 40.3 x 1013 cubic meters of evaporation from the ocean
ET = 6.54 x 1013 cubic meters of evapotranspiration from land areas
Q = 3.32 x 1013 cubic meters of streamflow and runoff from land surfaces and groundwater to the ocean

For land areas the budget would be, in units of 1013 cubic meters:

$$P = ET + Q \text{ or } 9.86 = 6.54 + 3.32$$

For the ocean, streamflow and runoff are inputs so that the budget in 1013 cubic meters is changed to:

$$P + Q - E = 0, \text{ or } 36.98 + 3.32 - 40.3 = 0$$

During periods of glaciation, however, a net increase in storage of water in the form of ice would occur in the polar regions and would be followed by periods with a net reduction in storage.

Water budgets for the different continents indicate the abundance of precipitation and streamflow for each continent as a whole (Table 2). By looking at the ratio ET/P we can also make relative comparisons of the abundance of water. A high ratio indicates a more arid climate (Australia), a lower ratio a more wet climate (Europe). Water budgets for such large areas do not tell us anything about the distribution of precipitation and streamflow within the continents. The unequal distribution of water supplies over continental areas and with respect to season results in many of our water resource problems. Thus, water budget studies are typically performed on river basins or individual watersheds, and often for time periods shorter than one year.

The Water Budget as a Hydrologic Method

The application of a water budget as a hydrologic tool is relatively simple; if all but one component of a system can either be measured or estimated, then we can solve directly for the unknown part. In the examples previously discussed, all components were known; in practice we usually do not have measurements for all budget components.

The annual water budget for a watershed or drainage basin is often used because of the simplifying assumption that changes in storage over a year period are negligible in many instances. Computations for the water budget could be made, beginning and ending with wet months (A – A') or dry months (B – B') as illustrated in Figure 3. In either case the difference in soil water content (storage) between the beginning and ending of the period is negligible. By measuring the total precipitation and streamflow for the year, the annual evapotranspiration (ET) can be estimated from the following:

$$ET = P - Q$$

Provided that a reasonable estimate of precipitation on the watershed is obtained, the next major assumption is that the total outflow of liquid water from the watershed has been measured. This implies that there is no loss of water by deep seepage to underground strata and that all groundwater flow from the watershed is measured at the gaging site. If certain kinds of geologic strata such as limestone underlie a watershed, the surface watershed boundaries may not coincide with the boundaries governing the flow of groundwater. In such cases there are two unknowns in the water budget, ET and groundwater seepage (L), which result in:

$$ET + L = P - Q$$

If losses to groundwater are suspected, they can sometimes be estimated by specialists in hydrogeology who have knowledge of geologic strata and respective hydraulic conductivities.

The change in storage can sometimes be difficult to quantify when we cannot assume that change in storage is negligible over the time interval. Estimates of change in storage become more difficult as computational interval diminishes and as the size of the area under investigation increases. The change of storage for a small vegetated plot may involve only periodic measurements of soil water content. Such measurements can be made gravimetrically (weighing a known volume of soil, drying the soil in an oven and reweighing), with neutron attenuation probes or other methods. As the size of the area increases, the storage changes of surface reservoirs, lakes and groundwater must also be considered. Stage–elevation–outflow data are needed to evaluate changes in lake or reservoir storage, and are not particularly difficult to analyze when compared with storage changes in surface soils and geologic strata.

The soil-water-storage component is usually distinguished from geologic strata in water budget computations, as that part which can be depleted by evapotranspiration. Diurnal as well as seasonal changes in storage of the soil mantle can be significant. The underlying geologic strata, on the other hand, represents a zone in which changes in storage are slow. Recharge and drainage account for changes in storage within strata below the soil mantle. These strata along with unconsolidated sand and gravel deposits are the sources of sustained streamflow yield (baseflow) from many watersheds.

Energy Budget

Solar energy is the driving force of the hydrologic cycle. As with the water budget, the components of the energy cycle can be identified and partitioned. Some of these components can then be related to parts of the water budget. The linkage between the water and energy budgets is direct; net energy available at the earth's surface is apportioned largely as a result of quantities of water in the various storage components. The primary purposes for studying the energy budget, like the water budget, are to develop a better understanding of the hydrologic cycle and to be able to quantify or estimate certain parts of the cycle. The energy budget has been widely used to estimate evaporation from bodies of water, the potential evapotranspiration for terrestrial systems, and has also been used to estimate snowmelt.

The earth's surface neither gains nor loses significant quantities of energy over long periods of time, but there may be a net gain or a net loss for any given time interval as determined by:

$$(S + s)(1 - a) + I - I = R_n$$

where

S = direct solar radiation (short-wave) in langleys

s = diffuse or scattered solar radiation (short-wave) in langleys

a = albedo or reflectivity to short-wave radiation (a decimal)

I = incoming long-wave radiation in langleys

I = outgoing long-wave radiation in langleys

R_n = net radiation in langleys

The net radiation is therefore the residual of incoming and outgoing short-wave and long-wave radiation. The albedo or reflectivity of the terrestrial system determines the proportion of total incoming short-wave radiation which is reflected back into the atmosphere. The albedos of several natural surfaces are listed in Table 3.

The apportionment of solar radiation is also affected by weather conditions. On the average, about 85 percent of the total downward stream of solar radiation is direct solar, but during cloudy days the diffuse or scattered short-wave radiation is the only short-wave input. Likewise, the long-wave radiation components are affected by atmospheric conditions. A cloudy or hazy atmosphere essentially traps long-wave radiation which would otherwise be lost from the earth, resulting in a larger incoming component (I) than an outgoing component (I). The emitting constituents of long-wave radiation in the atmosphere are primarily CO2, O3 and the liquid and vapor forms of water. Terrestrial objects absorb and radiate long-wave radiation very efficiently, approaching 100 percent. Therefore, reflectivity of long-wave radiation by terrestrial objects is considered negligible.

The net radiation (R_n) available at a surface is important from a hydrologic standpoint because it is usually the primary source of energy for evaporation, transpiration and snowmelt:

$$R_n = LE + H + G + P_n + S_n$$

where

LE = latent heat of vaporization multiplied by the total water evaporated (langleys)
H = sensible heat (langleys)
G = heat of storage, to the soil or underlying strata (langleys)
P_n = energy utilized in photosynthesis (langleys)
S_n = heat of fusion, energy used to melt snow (langleys)

Typically when snow is present, the majority of net radiation is apportioned to snowmelt (80 cal g^{-1}). In snow-free systems, the allocation of net radiation is highly dependent upon the presence or absence of water. If water is abundant and is readily available for evaporation and transpiration, then large amounts of energy are consumed in the evaporation process (about 585 cal g^{-1} at common terrestrial temperature). Little energy is left to heat the air (H) or ground (G). On the other hand, if water is limiting, LE is small and a greater amount of energy is available to heat the air, the ground surface and other terrestrial objects. Losses (or gains) of energy to the interior earth do not change rapidly with time and are usually negligible when compared to LE and H. Similarly, energy consumed in photosynthesis, although of unmeasurable importance to life on earth, is a very small quantity in hydrologic terms and is usually not considered.

The energy budget may be used to estimate evapotranspiration for conditions where water in the soil and plant system is abundant (not limiting), when horizontal advection is negligible and when Rn can be measured. In essence then, the energy budget estimates potential evapotranspiration which is governed only by available energy. For example, if we measured the energy budget components over a vegetated surface and soil water was not limiting to the plants the following estimate of evapotranspiration could be obtained:

If $R_n = 470$ ly day^{-1}

$H = 90$ ly day^{-1}

$G = 48$ ly day^{-1}

then, $LE = 470 - 90 - 48 = 332$ ly day^{-1}

and $E = 332$ ly day^{-1} / 585 cal gm^{-1} = .57 cm day^{-1}

Components of the energy budget are difficult to measure and as a result, several empirical relationships have evolved which allow one to estimate ET with more limited climatic measurements. Penman's (1948) equation is perhaps the most widely known approach used to estimate potential evapotranspiration (PET):

$$\text{PET} = \text{delta } R_n + \ E_a \ / \text{ delta} + \text{gamma}$$

where

delta = slope of the saturation vapor pressure - temperature curve at the air temperature
R_n = net radiation in langleys
E_a = a function of wind speed and vapor pressure gradient
and
gamma = constant

Measurements of wind speed, vapor pressure gradient, air temperature and net radiation require rather extensive instrumentation and are time consuming and costly. For most practical hydrology studies we do not have such climatic data available. Other methods require less extensive data, such as Thornthwaite's, which use only air temperature data. Monthly pan evaporation data may also be used to estimate PET with appropriate pan coefficients. With any of these methods we can only equate PET to actual ET when the soils have adequate water.

Water Budget Examples

Each watershed is a unique system which responds to precipitation and energy inputs according to its biological and physical characteristics. The following examples cover a variety of ecosystems and applications to provide the reader with some insight into the usefulness of the water budget method.

Tropical Ecosystems

The characteristics of tropical forests and watersheds require special considerations for water budget applications. High temperatures and abundant annual rainfall (usually more than 1500 mm) which is evenly distributed throughout the year, characterize the rainy tropics or tropical rain forests. Some tropical areas such as the northern Philippines, Burma and the east coast of Vietnam have distinct dry seasons, typical of the monsoon tropics. High altitude tropics likewise have strongly contrasting wet and dry seasons with distinct soil water changes and streamflow recessions. Soils are typically deep (usually more than 2 meters), stone-free, of uniform texture and structure, and well drained. Vegetation is dense and multi-layered with the result that only about one-third of all rainfall penetrates the forest canopy.

Streamflow yield and other components of the hydrologic cycle can be obtained for tropical ecosystems by using a water budget to couple climatological records with knowledge of the watershed system. Average soil texture and depth, and the rooting depth or extent to which the existing forest community can deplete soil water should be known. Generalized relationships of soil texture and "plant available water" (Figure 4) can then be used with estimates of soil depth to obtain values of the total soil water holding capacity and the total water available for evapotranspiration. For most tropical forest ecosystems, roots are assumed to fully occupy the soil system and evapotranspiration is considered to occur at or near the potential rate. Estimates of potential ET and rainfall are then coupled with the above soil-plant characteristics to provide an accounting of water surplus or deficit for given time increments.

An example of mean monthly water budgets based on climatological data from two different areas in Thailand is presented in Table 4. The mean monthly rainfall (item 1) is the input item of the accounting method. Potential ET for each month is listed as item 4. Actual ET (item 5) is either the total available moisture (item 3) or the potential ET (item 4), whichever is smallest. The available soil water is determined as the difference between field capacity and permanent wilting point. The quantity of soil water available to plants when soils are fully recharged for Chanthaburi and Chiang Mai are 279 mm and 124 mm, respectively. The first month's calculation, without actual soil-water content data, would appear to be somewhat of a guess. Errors associated with unknown antecedent soil water status can be minimized, however, if the accounting begins with a month in which the soil is typically recharged with water. The month which ends the rainy season, in these examples October, is a good starting month. The total available moisture (item 3) is determined from the sum of the rainfall and the initial soil moisture content (item 2). The remaining available moisture (item 6) is determined as the difference between total available moisture and actual ET. Any amount in item 6 which is in excess of the soil-water capacity is calculated as runoff in item 8.

Historical data rather than mean monthly values can be analyzed in a similar manner as Table 4, if we were interested in evaluating the water yield associated with some observed sequence of rainfall, perhaps a drought period. Water budget analyses of drought sequences are useful for determining storage requirements for water supply or hydroelectric reservoirs. Likewise, sequential monthly values for several years could be analyzed "before and after" some management activity which affects the actual ET. For example, the effect of clearcutting on water yield can be estimated by changing the effective rooting zone in the soil system after clearcutting and recomputing the water budget. Approximate effects on water yield may then be obtained as the results of a modified "effective soil water storage capacity."

A water budget analysis is only as good as the input data and the assumptions which have been made. Such assumptions include: (1) there are no deep seepage losses or "leakage" from or to the system, (2) transpiration responses are linearly related to available soil water content (unless better knowledge of physiological responses is available), and (3) rainfall intensities do not affect the volume of runoff, i.e., runoff only occurs when field capacity is exceeded. The assumption on leakage is always difficult to evaluate. Likewise, the manner in which the community of forest species respond to diminishing soil water content is unknown. The third assumption for tropical forest ecosystems is likely valid because of the extremely high infiltration capacities of soils.

Plot Studies

Small plots may be useful for water budget studies in remote areas. Plot studies have several advantages: (1) they are relatively easy and inexpensive to establish, (2) with proper care, all factors affecting the budget can either be measured or estimated, and (3) they can be useful to compare the effects of different soil and vegetation characteristics on water budget components. The major difficulty with plot studies is that their results or relationships are difficult to extrapolate to a larger watershed system or river basin. An example of a plot study is given below.

Pereira (1973) compared the actual evapotranspiration of three different tropical species on the basis of soil water sampling on plots. A natural bamboo thicket (Arundinaria alpina), Monterrey cypress (C. macrocarpa) and radiata pine (P. radiata) plantation were compared. Gypsum block electrical resistance gauges were used to measure soil water content in the root zone (upper 3.2 m). No surface runoff occurred and soil water measurements were taken after free water drainage. Rainfall and soil water changes were then used to estimate water use by trees. These plot studies indicated that the ratio of actual ET to free water evaporation (E0) were quite uniform, i.e., .86, repeated tests for a given cover type in a region, then such ratios can be used to estimate ET directly from PET estimates instead of the more laborious soil water sampling.

In a similar study, but on a warmer and drier site, Pereira (1973) estimated actual ET of a bamboo thicket to be approximately 0.85 E0. The excess water available to recharge groundwater was of interest in this case and was estimated with an annual water budget (Table 5). Five out of the eight years showed excess water available for groundwater recharge.

Such an approach is quick, but the validity of using ET = 0.85 E0 may not be valid for all years, particularly years which contain long dry periods. If more accurate estimates are desired, soil water content should be sampled periodically.

Watershed Studies

Although plot studies are useful for comparative purposes, they cannot be used directly to quantify the hydrologic response of a watershed. Likewise, plot studies cannot be used to represent the total watershed response to land-use changes which may include numerous activities spatially distributed over the area. It is often necessary, therefore, to instrument and determine a water budget of a control and a "treated" watershed in order to quantify the integrated hydrologic effects of some "treatment" or management activity. The following is an example of such a study.

Much of the densely forested hills south of Lake Victoria, Kenya has been cleared and planted to tea. Pereira (1973) and Blackie (1972) used a water budget to estimate the effects of such clearing on the seasonal pattern of streamflow and total yield. Two parallel forested watersheds were instrumented, one 700 ha and the other 540 ha. After one year of measurements, 120 ha of the 700 ha Sambert watershed was cleared and tea was planted; within four years, 350 ha of tea were planted. This planting was also accompanied by the development of roads, housing and a factory.

The following data were collected: daily streamflow, daily rainfall, Penman estimates of potential evapotranspiration, soil water content changes in the root zone, and changes in storage below the root zone as estimated from base-flow recession curves. Actual ET for both watersheds was determined from:

$$ET = P - Q - \text{delta } S - \text{delta } G - L$$

where ET, P, Q, and #S are as previously defined and

delta G = changes in storage below the root zone

L = any possible net loss of groundwater other than by streamflow.

The ET estimates from above were compared with Penman's potential ET. The initial clearing reduced ET by 11 percent, but over the first eleven years the average annual ET values were the same for cleared and control watersheds. Both watersheds exhibited an ET/PET ratio of 0.8. Therefore, the modifications to the watershed did not have any major effect on water yield except for the initial clearing.

Checks for leakage in this study consisted of comparing apparent water loss (P – Q) with Penman's PET. If P – Q had exceeded PET substantially, leakage would have been suspected.

Such watershed studies, if performed on representative sites, may be used as indicators of the total hydrologic response to some form of land use. Just as with plot studies, however, the extrapolation of results to other areas must be done with caution.

Brushland Watersheds

Chaparral vegetation covers extensive mountainous watersheds in the southwestern United States, watersheds which have hydrologic characteristics typical of semi-arid climates in other continents. Vegetation is shrub-like and includes Quercus and Ceanothus species. Potential evapotranspiration demands are high when compared to annual precipitation resulting in low annual streamflow yield. Flash floods, however, are not uncommon and result from high intensity summer rainstorms. Serious erosion and sedimentation problems are also common. Frontal-type precipitation in the winter months provides the majority of annual precipitation with some snow in the higher elevations. Winter precipitation may be followed by several months with little or no rainfall until late summer convective storms occur. Thus, soil water storage becomes substantially depleted over the growing season.

Mean annual precipitation in the Arizona chaparral varies from 400 to 635 mm. Annual water budgets for three chaparral watersheds in Arizona are presented in Table 6.

An interest in increasing water yield in Arizona led to several studies which considered the replacement of deep rooted chaparral shrubs with shallow rooted grasses. Such changes in vegetation type effectively reduce the magnitude of soil water storage which can be depleted by plant roots. Conversion to grasses took place on one of the Three Bar watersheds resulting in a reduction in evapotranspiration losses and a subsequent increase in water yield for ten years following conversion. For the ten-year period, mean annual streamflow was 216 mm as compared to 39 mm that would have been expected under chaparral vegetation. Contrasting annual estimates of ET before and after conversion tell us that ET was reduced from 614 mm (653 – 39) to 437 mm (653 – 216). In addition to the annual increase in water yield, streams which were intermittent began to flow throughout the year.

Boreal Forest — Peatland Ecosystems

Peatlands cover large areas in the boreal forests of North America, Europe and the Soviet Union as well as in many other locations throughout the world. In general they occur where topography is flat and where precipitation exceeds potential evapotranspiration. Peatlands have shallow water tables and consequently the evapotranspiration losses approach potential rates. Because these peatlands are integrally tied to regional and perched groundwater systems, the harvesting of forest products, including the peat itself, can affect the hydrologic response of such areas. The water budget can be used to gain a better understanding of these hydrologic systems under undisturbed and managed conditions.

This example was taken from work by Bay (1967) in which two perched peatlands in northern Minnesota were instrumented and water budgets developed. The watersheds were 3.2 and 2 hectares,

18

contained peat bogs with soils of from 1 to 8.5 meters deep and were isolated from the regional water table with minimal seepage losses. Upland mineral soils supported aspen (*Populus tremuloides*) and peat soils supported black spruce (*Picea mariana*). Changes in soil water storage of upland soils were not measured; however, these soils are typically fully recharged at spring and again at late fall. Thus, a water budget could be computed between spring and late fall with the assumption that #S = 0. For the peat soils, differences in water storage over a period of time were determined from records of recording wells. Changes in the elevation of the water table were converted to water storage by determining water yield coefficients for the horizons within the peat soil. The following water budget was then used to estimate evapotranspiration losses (ET) from the watersheds:

$$ET = P - Q - S_b$$

where S_b = change in water storage within the peat soil, based on wat. table changes

The water budget, computed for the growing season of six individual years, characterized the hydrologic response of these watersheds (Table 7). Actual ET values, as determined from the water budget, were compared to the potential ET as calculated by the Thornthwaite method. Estimates of ET were reasonably close to potential ET for half the years. High air temperatures and dry conditions during 1961 and 1963 were explanations for actual ET being much lower than potential ET.

During 1965 actual ET exceeded potential ET for both watersheds. This discrepancy was explained by excessive rainfall in September which probably resulted in deep percolation through mineral soils in the upland areas but was included in the water budget estimate of ET. Measurements of deep water tables in the area verified this explanation. Also, potential ET estimates were quite low because of cold air temperatures in August and September.

Water Budget Exercise

One hundred ninety hectares of mixed hardwoods are to be clearcut on a watershed which drains into a water supply reservoir. The city which received water from this reservoir is interested in determining how much of an increase in water yield might be expected as a result of this cut. In order to provide a conservative estimate of possible increases, a dry 21-month period was selected for analysis with a water budget. A water budget has been calculated for this dry period under pre-cut conditions (Table 8).

1. Using the following information and the same rainfall and potential ET data in Table 8, estimate the change in water yield in cubic meters for the 21-month period.
    a. Soils are clay-loam with an average depth of about 1.7 m; plant available water (field capacity minus permanent wilting point) averages 164 mm per meter of soil depth.
    b. The root systems of the mature hardwood stand fully occupy the soil; therefore, the total soil water which can be depleted by ET is 279 mm (1.7 m x 164 mm/m) as indicated in Table 8.
    c. Studies have shown that under light herbaceous plant cover, a condition similar to a clearcut area, soil water is depleted by ET only to a depth of about 0.6 m.
2. Discussion questions
    a. What assumptions were made in applying the water budget in this study?
    b. What factors would be important in determining the quantities of increased water yield which would be available at the reservoir site?

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Table 1. Approximate distribution of the earth's fresh water resources
(from Nace, 1964).

Hydrologic Storage Component	Percent of total fresh water
Polar ice and glaciers	77.35
Deep groundwater (>800 m)	11.05
Shallow groundwater (<800 m)	11.05
Freshwater lakes/streams	.34
Soil	.18
Atmosphere	.03

Table 2. Water budgets of the continents (from Todd, 1970).

Continents	P cm/yr	ET cm/yr	Q cm/yr	ET/P
Africa	67	51	16	.76
Asia	61	39	22	.64
Australia	47	41	6	.87
Europe	60	36	24	.60
North America	67	40	27	.60
South America	135	86	49	.64

Table 3. Albedos of natural surfaces (Budyko, 1956 as presented by Reifsnyder and Lull, 1965).

Surface	Albedo
Dry light sandy soils	0.25 - .45
Moist, grey soils	0.10 - .20
Dark soils	0.05 - .15
Meadows	0.15 - .25
Deciduous forests	0.15 - .20
Coniferous forests	0.10 - .15

Table 4. Average monthly water budgets for two stations in Thailand (taken from Holdridge et al. 1971).

Station: Chanthaburi, Thailand	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	YR
						mm							
1. Average rainfall	231	74	15	48	46	76	117	325	498	444	439	478	2791
2. Initial soil moisture	279	279	238	136	75	18	0	9	215	279	279	279	—
3. Total available moisture	510	353	253	184	121	94	117	334	713	723	718	757	—
4. Potential ET	123	115	117	109	103	110	108	119	123	128	129	124	1408
5. Actual ET	123	115	117	109	103	94	108	119	123	128	129	124	1392
6. Remaining available moisture	387	238	136	75	18	0	9	215	590	595	589	633	—
7. Final soil moisture	279	238	136	75	18	0	9	215	279	279	279	279	—
8. Runoff	108	0	0	0	0	0	0	0	311	316	310	354	1399

Station: Chaing Mai, Thailand													
1. Average rainfall	130	46	10	5	10	13	51	127	132	198	232	290	1244
2. Initial soil moisture	124	124	63	0	0	0	0	0	24	46	124	124	—
3. Total available moisture	254	170	73	5	10	13	51	127	156	244	356	414	—
4. Potential ET	114	107	102	99	85	87	87	103	110	117	120	112	1243
5. Actual ET	114	107	73	5	10	13	51	103	110	117	120	112	935
6. Remaining available moisture	140	63	0	0	0	0	0	24	46	127	236	302	—
7. Final soil moisture	124	63	0	0	0	0	0	24	46	124	124	124	—
8. Runoff	16	0	0	0	0	0	0	0	0	3	112	178	309

Table 5. Water budget for a bamboo thicket (taken from Pereira, 1973).

Water Budget Component	Year 1953	1954	1955	1956	1957	1958	1959	1960
				mm per year				
Rainfall	787	1295	940	1143	1372	1448	940	813
$ET = 0.85 E_o$	965	839	940	839	864	864	889	965
Balance available for recharge	−178	+456	0	+304	+508	+584	+51	−152

Table 6. Water budgets of three watersheds in Arizona (from Hibbert and Ingebo, 1971).

Watershed	Mean Elevation (ft)	Mean Annual Precip. (mm)	Mean Annual Q (mm)	Estimated Annual ET (mm)
Natural drainage	4600	467	30	437
Mingus	6300	503	5	498
Three Bar	3500	653	53	600

Table 7. Water budgets of two peatland watersheds in northern Minnesota over the growing season May 1 to November 1 (taken from Bay, 1967).

Watershed	Year	P (mm)	Q (mm)	S_b (mm)	ET (mm)	Potential ET* (mm)
S-2	1961	513	89	-54	478	537
	1962	578	152	-71	497	488
	1963	509	81	-37	465	527
	1964	597	165	-61	493	525
	1965	579	132	-66	513	443
	1966	572	141	-75	506	511
S-6	1965	575	104	-56	527	434
	1966	545	134	-89	500	511

* As calculated by the Thornthwaite method.

Table 8. Water budget exercise for a hardwood-covered watershed, before clearcutting.

	Year 1															Year 2					
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
											mm										
1. 1/ Average rainfall	58	103	133	98	100	48	27	4	31	42	36	12	50	120	140	105	90	95	65	20	48
2. 2/ Initial soil moisture	56	57	140	273	277	277	277	246	161	65	0	0	0	0	100	240	277	277	277	277	208
3. Total Available moisture	114	160	273	371	377	325	304	250	192	107	36	12	50	120	240	345	367	372	342	297	254
4. 3/ Potential ET	57	20	0	0	3	13	58	89	127	173	157	107	57	20	0	0	3	13	58	89	127
5. 4/ Actual ET	57	20	0	0	3	13	58	89	127	107	36	12	50	20	0	0	3	13	58	89	127
6. Remaining available moisture	57	140	273	371	374	312	246	161	65	0	0	0	0	100	240	345	364	359	284	208	127
7. 5/ Final soil moisture	57	140	273	279	279	279	246	161	65	0	0	0	0	100	240	279	279	279	279	208	127
8. 6/ Runoff	0	0	0	92	95	33	0	0	0	0	0	0	0	0	0	66	85	80	5	0	0

1/ Average over the watershed for each month of record.

2/ At start of each month. Same as "final soil moisture" of previous mon[illegible]

3/ Average annual values for the month, as estimated by Thornthwaite's meth[illegible]

4/ Total available moisture, or potential ET, whichever is smaller.

5/ At end of month. Same as "initial soil moisture" for next month. This value cannot be larger than the soil-water holding capacity determined for the watershed, for this watershed 279 mm.

6/ Runoff occurs when the remaining available moisture exceeds the water holding capacity for the watershed (279 mm).

Figure 1. The hydrologic cycle.

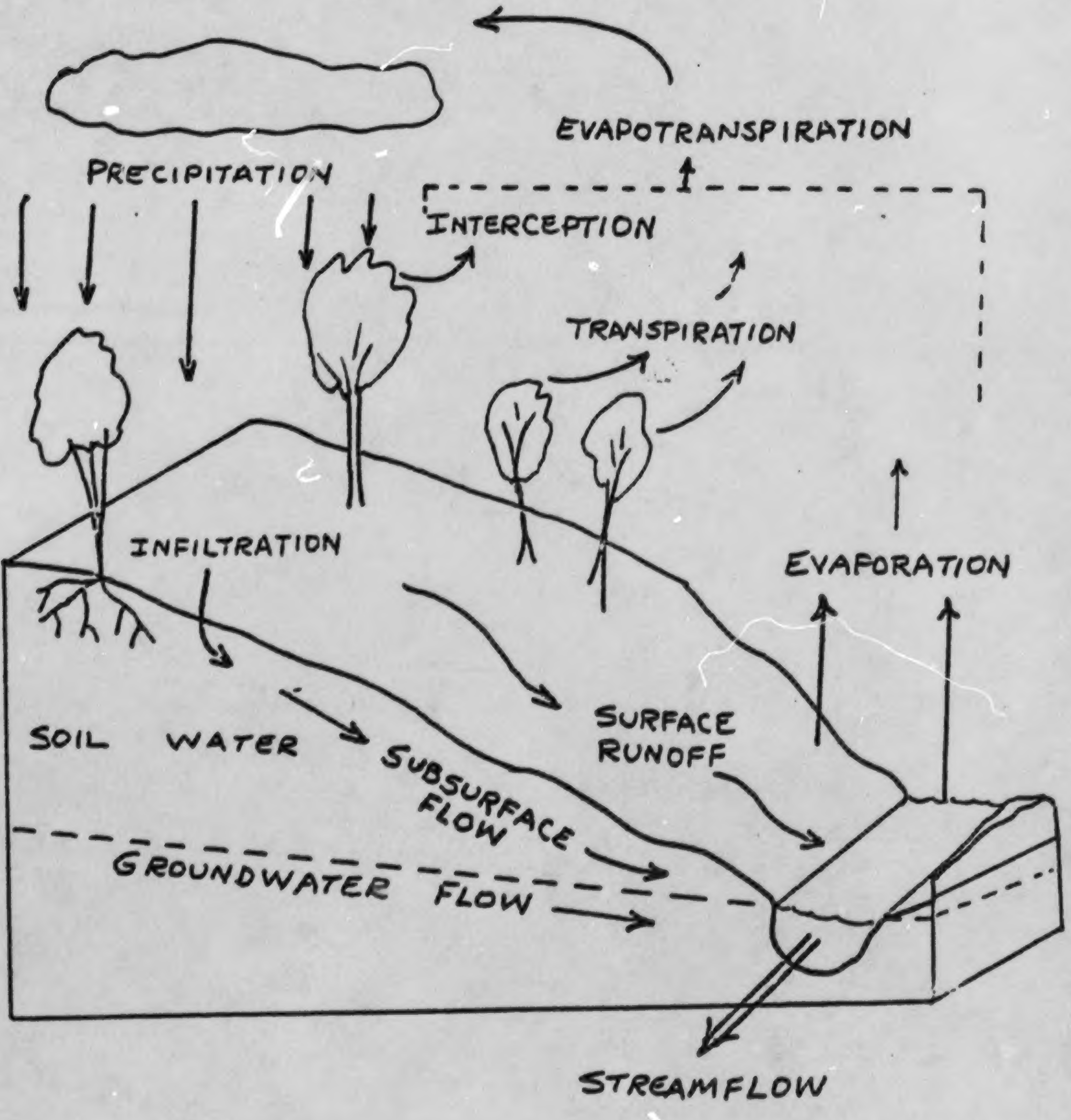

EVAPOTRANSPIRATION
PRECIPITATION
INTERCEPTION
TRANSPIRATION
INFILTRATION
EVAPORATION
SOIL WATER
SUBSURFACE FLOW
SURFACE RUNOFF
GROUNDWATER FLOW
STREAMFLOW

Figure 2. Hydrologic components of a watershed system (taken from Anderson et al. 1976)

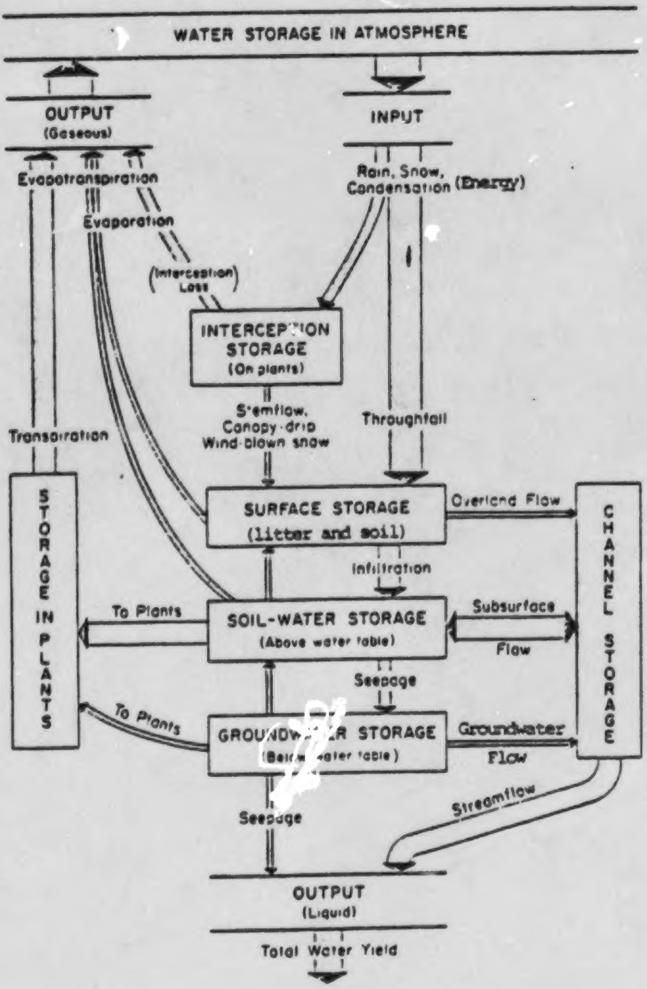

WATER STORAGE IN ATMOSPHERE
OUTPUT (Gaseous)
INPUT
Evapotranspiration
Evaporation
(Interception) Loss
Rain, Snow, Condensation (Energy)
INTERCEPTION STORAGE (On plants)
Stemflow, Canopy-drip Wind-blown snow
Throughfall
Transpiration
STORAGE IN PLANTS
SURFACE STORAGE (litter and soil)
Overland Flow
CHANNEL STORAGE
Infiltration
To Plants
SOIL-WATER STORAGE (Above water table)
Subsurface Flow
Seepage
To Plants
GROUNDWATER STORAGE (Below water table)
Groundwater Flow
Seepage
Streamflow
OUTPUT (Liquid)
Total Water Yield

Figure 3. Hypothetical fluctuation of soil moisture on an annual basis.

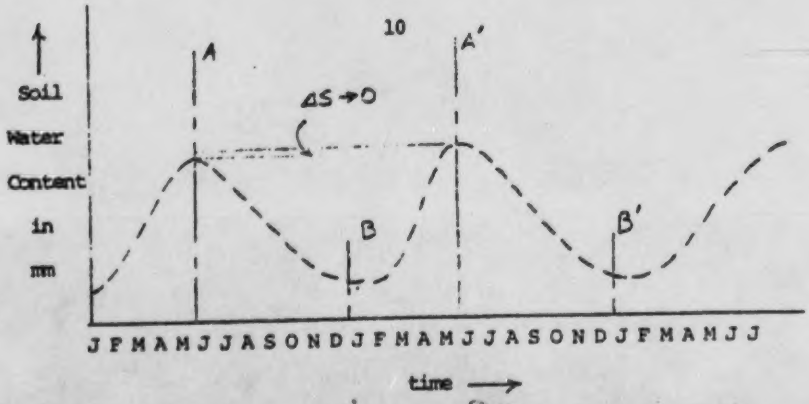
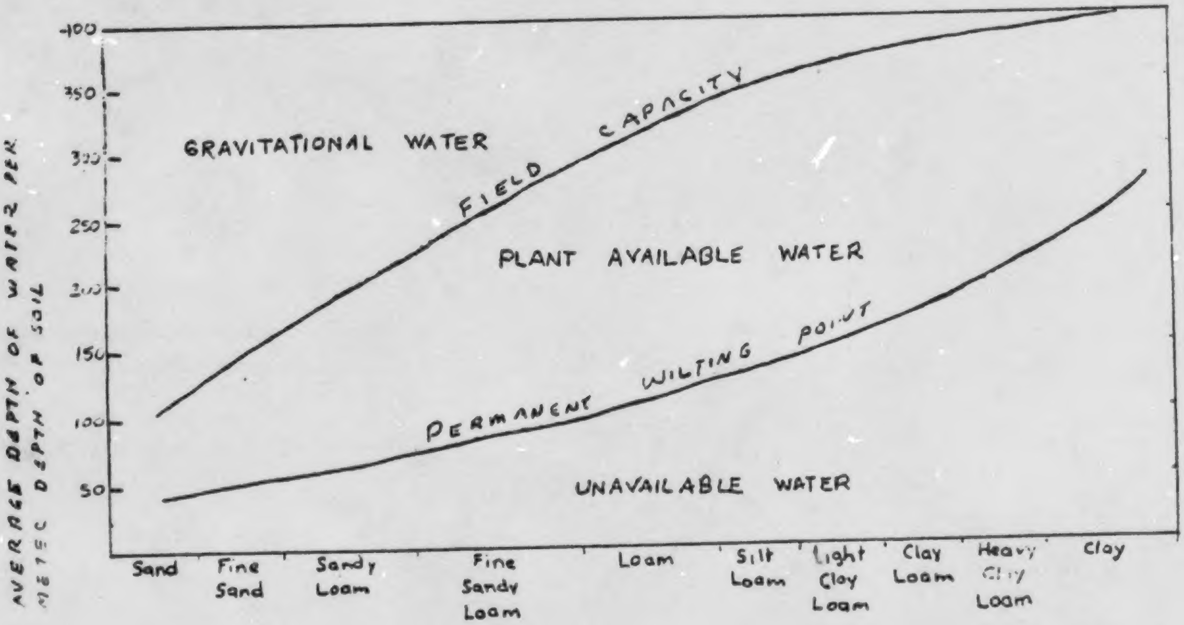


Figure 4. Typical water characteristics of different-textural soils (adapted from USDA, 1961)



Hydrologic Processes

The hydrologic and energy budget concepts discussed in the previous section provide the basis for a more detailed look at the various hydrologic processes. Before we can truly understand hydrology and be able to predict the hydrologic consequences of land management activities, we must understand the processes which govern the flow and storage of water within the soil-plant-atmosphere system.

Precipitation

Precipitation is the component of the hydrologic cycle with which most people are familiar. We read about precipitation amounts and forecasts on a daily basis. As a process, however, most people have a cursory understanding of why precipitation occurs and why it occurs where it does. Hydrologists view precipitation as one of the major input components of a hydrologic study or watershed system analysis. Although its importance to any hydrologic study is readily acknowledged, we seldom have adequate precipitation data. Precipitation data networks need to be designed and put into the field so that we can get the information where we need it, and when we need it. It is essential that we understand the precipitation process and the factors which influence the amount and distribution of precipitation over an area before such networks can be developed.

Precipitation occurs when three conditions in the atmospere are met: (1) the atmosphere becomes saturated, (2) small particles or nuclei are present in the atmosphere upon which condensation or sublimation can take place, and (3) water or ice particles must coalesce and grow large enough to fall under the influence of gravity. Saturation results when either the air mass is cooled until the saturated vapor pressure is reached or when moisture is added to the air mass (Figure 1). Rarely does the direct introduction of moist air cause precipitation. More commonly precipitation occurs when an air mass is lifted, becomes cooled, and reaches its saturated vapor pressure. Air masses are lifted as a result of (1) frontal systems, (2) orographic effects, or (3) convection. Different storm and precipitation characteristics result from each of these lifting processes.

Frontal precipitation occurs when two air masses of different temperature and moisture content are brought together by general circulation and air becomes lifted at the frontal surface. A cold front results from a cold air mass replacing and lifting a warm air mass. Conversely, a warm front results when warm air rides up and over a cold air mass. Cold fronts are characterized by high intensity rainfall of relatively short duration and usually have less areal extent than warm fronts. Widespread, gentle rainfall is more characteristic of warm fronts.

Orographic precipitation occurs when an air mass is forced up and over mountain ranges as a result of general circulation. As the air mass becomes lifted, a greater volume of the air mass reaches saturation vapor pressure resulting in a general increase in precipitation with increasing elevation. Once the air mass passes over mountains a lowering and warming of the air occurs. This results in a rain shadow effect on the leeward side of mountain ranges.

Convective precipitation, as characterized by summer thunderstorms, is the result of excessive heating of the earth's surface. When the air adjacent to the surface becomes warmer than the air mass above, lifting occurs. As the air rises and condensation takes place, the latent heat of vaporization is released, more energy is added to the air mass and consequently more lifting occurs. Rapidly uplifted air can reach high altitudes where water droplets become frozen and hail forms or becomes intermixed with rainfall. Such rain or hail storms are of the most severe precipitation events anywhere. High intensity, short duration rainfall over rather limited areas characterize convective storms. Numerous thunderstorms can occur over a widespread area, however, and can cause flash flooding.

Interception — Net Precipitation

Once rainfall or snowfall has occurred, the type, extent and condition of vegetation can strongly influence the disposition and amount of precipitation reaching the soil surface. Dense coniferous forests in northern latitudes and the multi-storied canopies of the tropics can catch and store large quantities of precipitation which ultimately evaporate and are lost from the watershed. In the tropics, over 70 percent of the annual precipitation may be lost via interception. As we proceed to more arid or semi-arid environments, and more sparse vegetation, the interception losses become less important. Table 1 summarizes interception losses of different vegetation types. Although we generally consider forests to have the highest interception losses, grasses may intercept 10 to 20 percent of gross precipitation during periods when maximum growth has been attained.

Not all the precipitation which is caught by a forest canopy is lost to the atmosphere. Much may drip off the foliage or run down the stems and thereby reach the soil surface. Conversely, not all the precipitation that penetrates the forest canopy becomes available for either soil water or runoff. The litter which accumulates on the forest floor can store large quantities of precipitation which ultimately evaporate.

The amount of intercepted precipitation which is not available at the soil surface is defined as:

$$I = P_g - T_h - S_f$$

where: I = interception loss in mm or inches
P_g = gross precipitation in mm or inches
T_h = throughfall in mm or inches
S_f = stemflow in mm or inches

The partioning of a given quantity of rainfall into the above pathways is determined by the kind and amount of vegetative cover. If we were to observe the interception process of a growing forest from seedling stage to mature forest we would see that (1) T_h would diminish over time as the canopy cover increases, (2) S_f would increase over time, but would be rather small, and (3) the storage capacity of vegetation and litter, as related primarily to leaf surface area, would increase substantially. In general, conifer forests have a greater storage capacity (2mm) than hardwoods (1 mm). We must recognize, however, that the total interception loss from a forest stand is the result of not only canopy interception, but also that of understory shrubs, grasses and forest floor materials.

If interception losses were determined for individual storms, we would see that the precipitation and associated storm characteristics influence the interception process as well as vegetation characteristics. The type of precipitation, whether rain or snow, the intensity and duration of rainfall, wind velocity and evaporative demand affect interception losses associated with individual storms. The interception of snow, although clearly visible for a conifer forest immediately after snowfall, is usually not considered to be a significant loss. Much of the snow caught by foliage reaches the soil surface by the mechanical action of wind or by melt and drip. The process of interception during a rainstorm usually results in greater losses than with snowfall and can be visualized as in Figure 2. The total interception loss is determined by both the evaporative demand during the storm and the storage capacity of the vegetation. If a storm were to last over a long period of time under windy conditions, we would expect the interception loss to exceed that from a storm of equal duration but with calm conditions. Conversely, a high intensity, short duration thunderstorm with high wind speeds may have the least amount of interception loss. This would be explained by the action of wind which could mechanically remove water from the canopy and, therefore, not allow the storage capacity of the canopy to be reached. With the short duration, the effects of wind on evaporative loss would be minimal.

The hydrologic importance of interception as a loss component of the water budget of a watershed is dependent upon several climatic, physical and vegetative characteristics. Because both the evaporation of intercepted water and transpiration are energy dependent processes, the total evapotranspiration (ET) loss for a period of time may be about the same for either process under the same climatic conditions. Therefore, the evaporation of intercepted water woud not be a total "loss" if balanced by a reduction in transpiration which would have ocurred had the canopy been dry. This reasoning is valid only if rainstorms occur during periods when active transpiration would have otherwise been taking place.

In most water budget studies, interception loss is considered to be an important storage term which should be subtracted from gross precipitation. The result is net precipitation, or that amount of precipitation that is available to either replenish soil water deficits or become surface, subsurface or groundwater flow out of the system. Net precipitation can be determined from:

$$P_n = P_g - I$$

where: P_n = net precipitation in mm
P_g = gross precipitation measured by rain gauges in openings, in mm, and
I = interception loss in mm.

For simple plot studies, the above terms can be measured rather easily. An evaluation of net precipitation over a watershed can, however, be quite complex. The spatial variability of canopy cover type and extent, canopy stratification or layering and the storage capacity of plant litter all affect the total interception loss for a watershed. Under certain climatic conditions, the interception storage differences between species can result in water yield differences. In regions where annual precipitation exceeds potential evapotranspiration (ET) and soil water rarely limits transpiration, differences in water yield may be observed between say conifers and hardwoods. Converting from hardwoods to conifers in the humid southeastern United States, for example, has resulted in significant reductions in annual streamflow volume (Swank and Miner, 1968). Such differences would not likely be observed in semi-arid regions because of the higher ratio of annual potential ET to annual precipitation. The reasoning is that the difference in precipitation reaching the soil surface, due to differences in interception, will on the average satisfy soil water deficits. Thus, these differences in net precipitation will simply be transpired at some later time.

The effects of forest canopies on the disposition of precipitation, particularly snow, also have management implications for water yield improvement. Snow has a high surface area to mass ratio and consequently is highly affected by wind patterns. Small openings within a conifer stand, for example, experience eddies which deposit more snow than the adjacent forest. Also, much of the snow intercepted by surrounding trees becomes mechanically deposited into these openings by wind. Studies have indicated that by clearcuttng strips in conifer stands and orienting them perpendicular to wind, the deposition of snow can be increased within the strips. In some cases this increased accumulation results in an increase in water yield.

Up to this point in our discussion, interception has been considered a loss from a watershed. In some coastal areas, however, fog may be intercepted by vegetation foliage and by means of coalescence and drip, may be added to the soil. In such cases, the greater the surface area, the greater the inercepton input to the water budget.

Movement of Water Into and Through the Soil

The rate of net precipitation, once it reaches the forest floor or soil surface, depends upon the soil surface conditions and the physical characteristics of the soil itself. Of primary interest are those factors which affect the rate at which water can enter the soil and the subsequent rate of movement through the soil.

Plant material or litter on the soil surface influences the amount and rate of movement of water into the soil surface. Litter can be viewed as two hydrologically distinct layers: (1) an upper horizon composed of leaves, stems and other undecomposed plant material, and (2) a lower horizon of decomposed plant material which behaves much like mineral soil. The upper horizon protects the soil surface from the energy of raindrop impact which could displace smaller soil particles into voids and effectively seal the soil surface. Plant debris also acts to detain any surface runoff which might occur and in effect minimizes overland flow. The lower horizon has a substantial storage capacity, over 200 percent by weight in some instances. Thus plant litter is important as both a storage component and as a protective cover which maintains an "open" soil surface condition favorable for high rates of water entry into the surface.

The process by which water enters the soil surface is called infiltration. Infiltration results from the combined forces of capillarity and gravity. If we applied water to a dry, medium textured soil, a very rapid initial infiltration rate would be observed (Figure 3). This high initial rate is due to the strong physical attraction of soil particles to water (capillarity). As time proceeds and the soil water content increases, the rate of infiltration eventually becomes a constant. At this time, infiltration is only as rapid as the rate which the soil can drain under the influence of gravity. The process of saturated flow through the soil mantle under gravitational forces is called percolation.

The flow of water through unsaturated or saturated soils can be described by Darcy's law which states:

$$Q = k\ A\ (\text{delta}\ H/L)$$

where Q = flow per unit time ($\text{cm}^3\ \text{sec}^{-1}$)
k = coefficient of permeability for saturated flow or hydraulic conductivity for unsaturated flow ($\text{cm}^3\ \text{cm}^{-2}\ \text{sec}^{-1}$)
A = cross-sectional area through which flow occurs (cm^2)
delta H/L = hydraulic head gradient (delta H) across the length (L) of flow path ($\text{cm}\ \text{cm}^{-1}$)

In the case of saturated flow, the coefficient of permeability (k) is a constant. For unsaturated flow, the hydraulic conductivity (K) is used instead of k and varies with the water content in the soil.

The infiltration capacity of a soil (f_m) is the maximum rate at which water can enter the soil surface. At any point in time, the infiltration capacity of a soil depends on soil water content and other physical conditions such as the presence of soil frost. Actual infiltration rates equal f_m only when rainfall or snowmelt intensity equals or exceeds f_m ($t_2 - t_3$ in Figure 4). In this case, the soil water content was high and rainfall intensity (R_1) exceeded infiltration capacity resulting in surface runoff or ponding. The same rainfall intensity at a time of drier soil ($t_0 - t_1$) would result in no surface runoff because the infiltration capacity is greater than the rainfall rate, thus actual infiltration rate equals rainfall rate.

Forest soils are characterized by high infiltration capacities which are rarely exceeded by rainfall intensity. Forest soils have rough surfaces and contain many large channels or pores in addition to the interpore spaces associated with soil texture and structure. Soils associated with other types of vegetation, in general, have lower infiltration capacities than forest soils. A comparison of net infiltration rates (that part of the infiltration curve which becomes constant) for various vegetation and soil characteristics are illustrated in Table 2. The importance of the storage capacity of a soil is clearly evident, e.g., even sandy soils with forest cover have low infiltration rates if the soil is shallow and underlain by bedrock.

Evapotranspiration

Evaporation from soils, plant surfaces and water bodies, and transpiration through plant stomata are often considered collectively as evapotranspiration (ET). Evapotranspiration is of particular interest to watershed managers because it strongly affects the water yield characteristics of an area and is often influenced by forest and range management practices.

The evaporation process is simply the net loss of water from a surface by means of a change in state of water from liquid to vapor. The requirements for evaporation or transpiration are:

(1) a flow of energy to the evaporating or transpiring surface;
(2) a flow of vapor away from these surfaces; and
(3) a flow of liquid water to these surfaces.

If one or more of these flows are changed, there is a corresponding change in the total ET loss from a surface. Conditions that control the net flow of energy by radiation, convection, and conduction to evaporating surfaces determine the amount of energy available for the latent heat of vaporization. The albedo or reflectivity of the evaporating surface determines the proportion of incident solar radiation that is absorbed by the surface. This absorbed solar radiation plus the net longwave radiation constitutes the net all-wave radiation which is available to evaporate water, heat the air, or heat the soil system. When water is readily available, most of this net radiation is utilized in the ET process. Some studies have shown that over 80 percent of net radiation is utilized in ET for well-watered soils with a dense vegetative cover. As water becomes limiting a greater proportion of the net radiation goes into heating the air and soil surfaces.

The ways in which net radiation becomes allocated to ET or other processes can be clearly illustrated if we consider the "oasis effect." Oases are islands of vegetation which have adequate water supplies (usually artesian springs) but are surrounded by desert. The net radiation in the barren desert is largely allocated to heating the soil surface and the air above, because water is not available. Very high soil and air temperatures result. Net radiation available at the oasis, however, may be entirely allocated to ET. In some cases, ET rates in oases exceed the potential ET*1 which is determined only by the net radiation. Such extremely high ET rates are caused by the addition of advected sensible heat from the surrounding desert area. The surface area of the foliage thus becomes important as a receptor of sensible heat which is added to the evaporating surface.

The flow of vapor away from a surface is initially a diffusion process from a region of high water concentration to a region of lower water concentration. The zone immediately above the evaporating surface through which only diffusion occurs is called the boundary layer. Above the boundary layer, water vapor is more rapidly transported away from the evaporating surface by mass movement due to turbulent eddy movement or wind. As wind and turbulence increase, the thickness of this boundary layer diminishes which increases the rate of vapor flow away from the surface. This explains the rapid evaporation rates observed during windy conditions.

Differences in the concentration of water in the atmosphere and the evaporating surface are measured as vapor pressure differences. The vapor pressure of a wet surface is a function of its temperature. The vapor pressure of the atmosphere is a function of its temperature and its relative humidity. Vapor flow occurs only when the vapor pressure of the evaporating surface exceeds that of the atmosphere. Thus, the vapor pressure gradient is the driving force of the evaporation process.

The flow of water, both liquid and vapor, through the soil-plant-atmosphere system is analogous to Ohm's Law. For a free-water surface the flow (current) is proportional to the vapor pressure gradient (voltage) and inversely related to resistance as follows:

$$E = V.P.D./r_{bl}$$

where E = evaporation flux
V.P.D. = vapor pressure gradient
r_{bl} = resistance to flow (boundary layer).

The major resistance to evaporation from a free-water surface is related to the thickness of the boundary layer. Under still air conditions, this resistance is large.

When we consider the flow of water through a soil-plant system the processes become more complicated. The flow of liquid water to the evaporating surface must equal the flow of vapor away from the surface for the evaporation or transpiration rate to be sustained. If water were readily available, the transpiration flux would equal:

$$T = * * / * r_i$$

where T = transpiration flux
$* *$ = water potential gradient
r_i = resistances within the soil-plant system.

Flow is always from a region of high water potential (high energy status) to low water potential (low energy status) as illustrated in Figure 5. The total water potential gradient, rather than strictly the vapor pressure gradient, is the driving force of water flow. The total flux is inversely related, however, to several resistances including the soil (r_{sl}) and those within the plant. As the soil dries, the area through which water can flow diminishes and consequently the resistance to flow increases. Within the plant, most resistances remain relatively constant, such as the root cortex (r_c), xylem (r_x), and the cuticle (r_{cu}) of plant leaves. The major "variable resistor" component of a plant system is the stomata (r_s). The stomata of plant leaves open and close in response to environmental factors such as light, CO_2 concentration, and soil-water content. Generally during daylight, stomata are open and plants transpire at rates proportional to the soil-water content. As soil water beomes limiting, stomata close (r_s becomes large) and transpiration ceases. When soil water is abundant and plant stomata are open, the flux of water again becomes dominated by the boundary layer (r_{bl}) only this time at the leaf-atmosphere interface.

The effects of different vegetation types on the water budget are apparent when we compare the evaporation of a bare soil with the transpiration of both a herbaceous-grass cover and a mature forest (Figure 6). As long as soil water is abundant in all three cover types, evaporation and transpiration will occur at rates primarily dependent upon the net energy available, the vapor pressure gradient and wind conditions. Once the soil begins to dry, however, the resistance to flow within the soil becomes large enough to reduce the flow of liquid water to the evaporating soil surface. Soil water depletion may only occur to depth "a" after a given period of time. Except for very coarse soils, evaporation seldom depletes soil water below 0.6 - 0.7 meter depth. With herbaceous vegetation the flow of water to the evaporating (transpiring) surface can continue for a longer time period because plant roots grow and extend into greater depths (b) and extract water which would otherwise not évaporate from the soil in the given time period. The deep rooted forest vegetation can extract water to depth "c" and will transpire until resistances to flow become large. Obviously, a greater volume of water can be extracted by the deeper rooted vegetation. These differences in soil-water depletion result in differences in water yield. Given a rain or snowmelt event, more water will be required to recharge the soil under forest vegetation than the soil with herbaceous cover. The least amount of water would be needed to recharge the bare soil. Consequently, the proportion of rainfall or snowmelt that will be yielded as streamflow will be greatest for the bare soil and least for the forested area. By removing forest vegetation or by converting from a deep-rooted species to a shallow-rooted species, annual ET losses can be reduced and water yield increased. The maximum changes in water yield for such conversions will be observed in areas with deep soils.

An example of the effects of thinning a forest stand on soil water content over an active period of transpiration is illustrated in Figure 7. For clearcutting operations, such differences in soil water storage would be over a larger area with a greater potential for increased water yield. As vegetation grows back onto the site, soil-water depletion will increase and water yield will be diminished.

Differences in transpiration rates and annual transpiration losses among different species of vegetation can be attributed to factors other than rooting depth. The albedo or reflectivity of a plant surface with respect to solar radiation can affect the energy available for transpiration. The length of the growing season or the period of active transpiration can differ among species and also result in water yield differences. For example, annual grasses typically have a very short growing season and become dormant quickly as soil water becomes limited. Some coniferous forests on the other hand may transpire over much longer periods of time even during winter months when temperatures are warm and soil water is available.

Runoff

Runoff refers to the various processes and pathways by which excess water becomes streamflow. Excess water represents that part of total precipitation which runs off the land surface and that which drains from the soil and is thus not consumed by ET. Some water flows rather quickly to produce streamflow yet other pathways have a detention storage time which may take weeks or months for excess precipitation to show up as streamflow. If we were to identify the major pathways of flow and compare these with a streamflow hydrograph[2] from a watershed, the runoff process can be somewhat simplified (Figure 8).

A perennial stream, i.e., one which flows throughout the year, is most likely being fed by groundwater, pathway "D" in Figure 8. This component sustains streamflow between periods of precipitation or snowmelt and represents the relatively constant baseflow part of a hydrograph. Because of the long and tortuous pathways involved, groundwater flow, hence baseflow does not respond quickly to moisture input.

Once rainfall or snowmelt occurs, several additional pathways of flow feed streamflow. The most direct pathway from precipitation to streamflow is that part which falls directly into the stream channel, called channel interception (A in Figure 8). This component causes the initial rise in the streamflow hydrograph and ceases soon after precipitation stops. Surface runoff or overland flow occurs from impervious areas or areas in which the rainfall rate exceeds the infiltration capacity of the soil (B). Some surface runoff is detained by the roughness of the soil surface, but nevertheless represents a quick flow response to moisture input, second only to channel interception. During a rainstorm, this component of the hydrograph would be relatively large for urban areas but typically insignificant for forested areas with deep soils.

Subsurface flow or interflow is that part of precipitation which infiltrates, yet arrives at the stream channel over a short enough time period to be considered a part of the storm hydrograph, illustrated as pathway "C" in Figure 8. This is considered to be the major contributing pathway of storm hydrographs from forested watersheds.

The sum of channel interception, surface and subsurface flow is called direct runoff or stormflow. Direct runoff is the part of the hydrograph of interest when we look at the flood-producing characteristics of most watersheds.

Although we can conceptually visualize the four major pathways of flow, subsurface flow is particularly difficult to quantify or separate from the others. Also, the actual pathway from rainfall to streamflow may in reality involve surface and subsurface flow. Water may infiltrate in one area and exfiltrate downslope and run over the land surface for some distance. Conversely, some surface runoff may collect in depressions in the land surface to be evaporated or infiltrated at some later time. By viewing the total streamflow hydrograph, therefore, we are seeing the total integrated response of a watershed to some quantity of moisture input.

In forested areas with deep soils, the primary source of stormflow is from subsurface flow. The mechanisms by which subsurface flow produces stormflow hydrographs have been explained by the variable source area concept. This concept states that direct runoff is the result of slope water movement and channel expansion (Figure 9). Slope water movement occurs by percolation and by the displacement of stored water. Thus, areas in depressions and areas adjacent to perennial, intermittent and ephemeral channels usually have higher soil water contents than upslope areas, and are the initial sources of stormflow. As rainfall continues a larger portion of the basin contributes. Some areas in the ridgetops of mountainous watersheds may never contribute to stormflow and would be considered recharge areas. As a rainstorm progresses, soils along stream channels become saturated and surface flow results. This surface flow typically "collects in draws to form intermittent and ephemeral channels which in turn increase the channel length during a large storm to perhaps ten or twenty times the perennial length" (Hewlett and Nutter, 1969). This channel expansion can reach areas upslope quickly which would otherwise not contribute to stormflow for a much longer time period.

The variable contributing area in forested watersheds has important implications with respect to the impacts of land use activities on water quality. Areas adjacent to stream channels, for example, would be the first areas to contribute dissolved and particulate material to streamflow. If we are concerned with the delivery of nutrients, chemicals, and sediments to streamflow, our management guidelines should focus on those areas which most likely contribute to runoff.

Notes

1. Potential ET is generally defined as the rate of evaporation and transpiration which would take place from a completely vegetated area and one in which soil water was not limiting.

2. A streamflow hydrograph is the graphical relationship of streamflow discharge (m^3/sec) plotted against time.

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Figure 1. Processes by which an air mass becomes saturated; (a) the moisture content of the air increases or (b) temperature decreases.

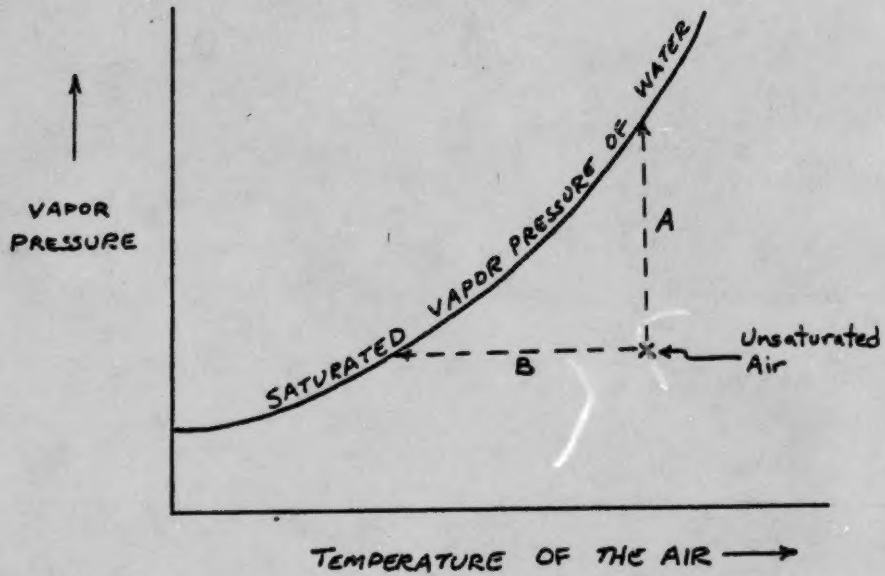

VAPOR PRESSURE
SATURATED VAPOR PRESSURE OF WATER
A
B
Unsaturated Air
TEMPERATURE OF THE AIR

Table 1. Selected interception losses from different vegetation types as a percent of gross precipitation (taken from Dunne and Leopold, 1978).

Vegetation	Median Interception (% of gross precipitation)
Deciduous forests	13
Coniferous forests	
North America	27
Europe	35
Alfalfa	36*
Oats	7*
Spring wheat	10-35*

* During growing season only.

36

Figure 2. Interception loss during a rainstorm (from Leonard, 1961).

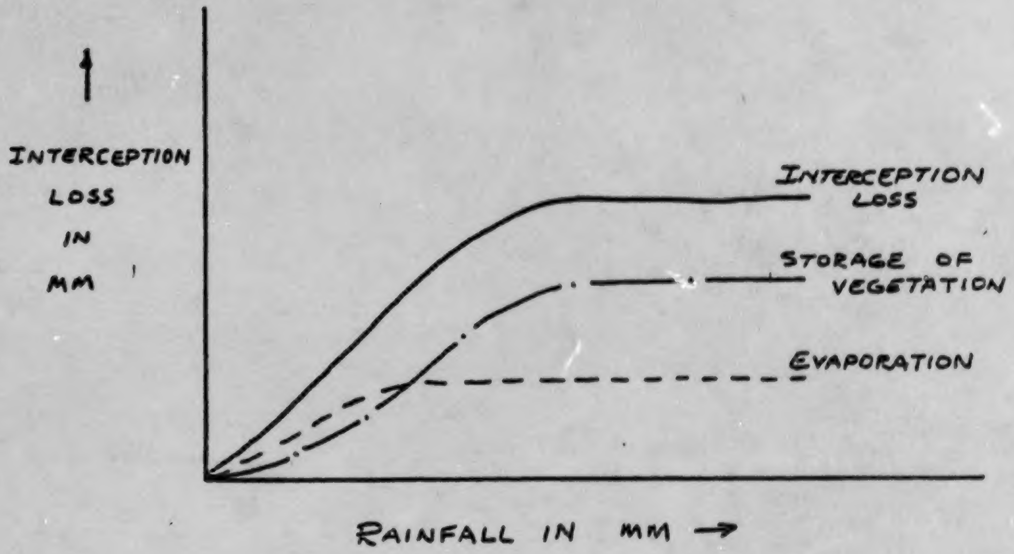


Figure 3. Infiltration capacity for an unfrozen mineral soil, illustrating the initial rapid infiltration due to capillarity (I) and the constant rate caused by gravity flow (II).

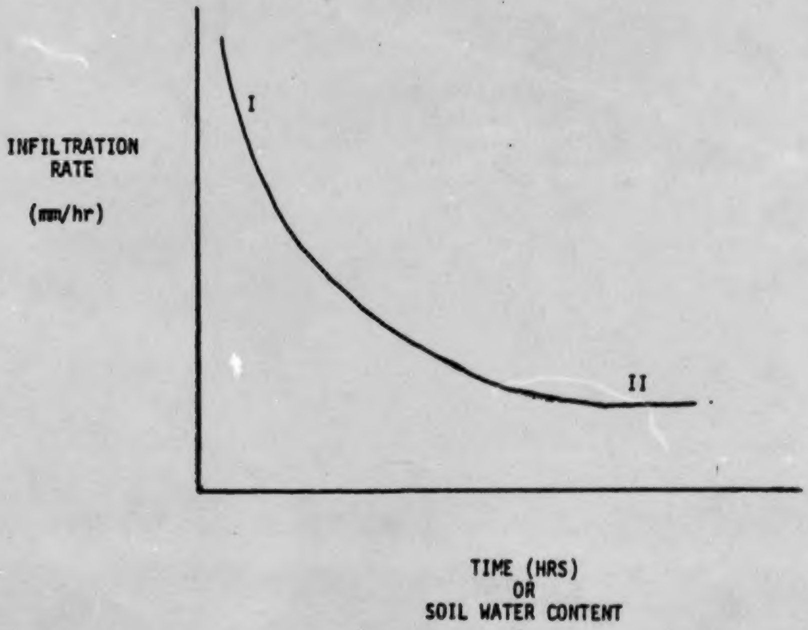


Figure 4. Relationships between infiltration capacity, rainfall intensity ano actual infiltration rates.

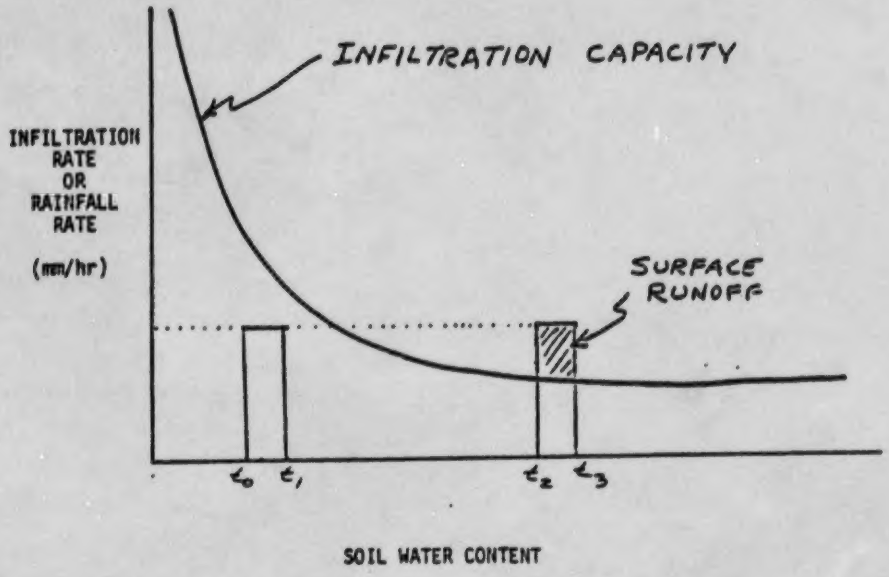


Table 2. Net infiltration rates in mm/hour for unfrozen soils (taken from Gray, 1970).

Soil Category	Bare Soil	Row Crops	Poor Pasture	Small Grains	Good Pasture	Forested
I	8	13	15	18	25	76
II	3	5	8	10	13	15
III	1	2	3	4	5	6
IV	<1	<1	<1	<1	<1	<1

I = Coarse-medium text. soils over sand or gravel outwash
II = Medium text. soils over medium text. till.
III = Medium and fine text. soils over fine text. till.
IV = Soil over shallow bedrock.

Figure 5. A diagrammatic representation of soil-plant-atmosphere resistances to water flow and the corresponding water

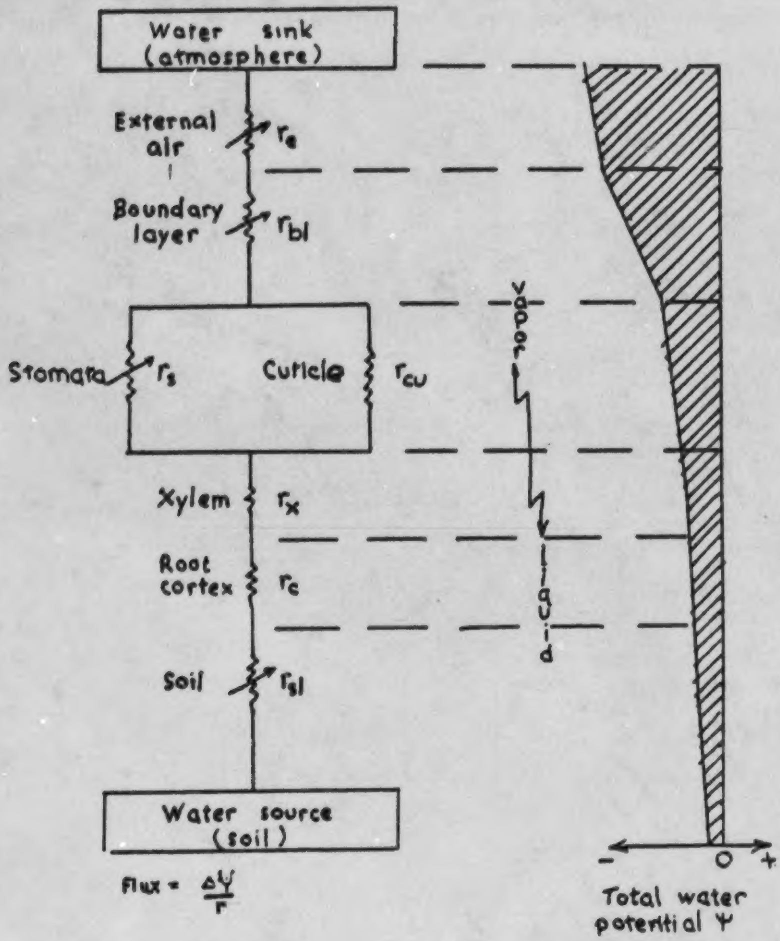

Water sink
(atmosphere)
External air
r_e
Boundary layer
r_{bl}
Stomata
r_s
Cuticle
r_{cu}
vapor
Xylem
r_x
Root cortex
r_c
liquid
Soil
r_{sl}
Water source
(soil)
Flux = $\frac{\Delta\Psi}{r}$
−
0
+
Total water potential Ψ

Figure 6. Comparison of soil-water depletion (cross-hatched area) of bare soil, herbaceous cover and forest cover.

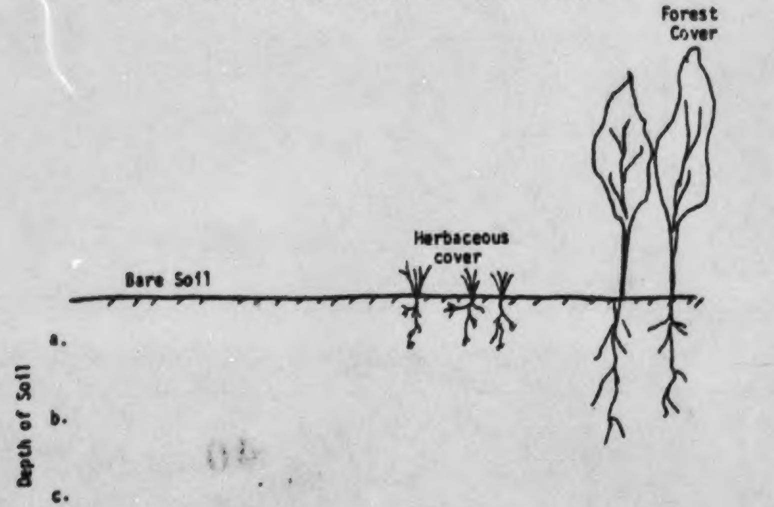

Forest Cover
Herbaceous cover
Bare Soil
a.
b.
c.
Depth of Soil

Figure 7. Comparison of soil-water distribution beneath a thinned and unthinned stand of loblolly pine (from Douglas, 1965).

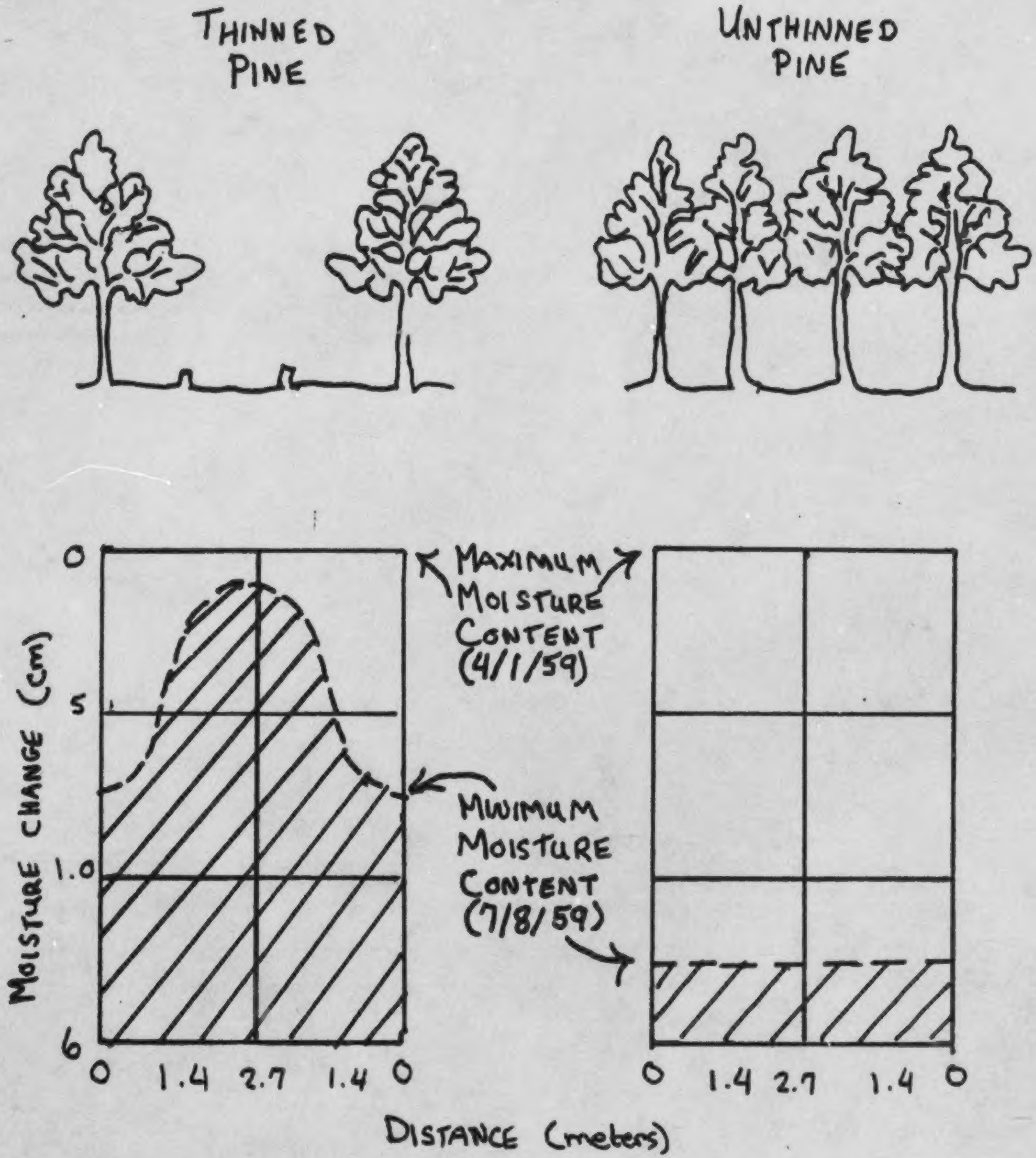


Figure 8. Relationship between pathways of flow from a watershed and the resultant streamflow hydrograph.

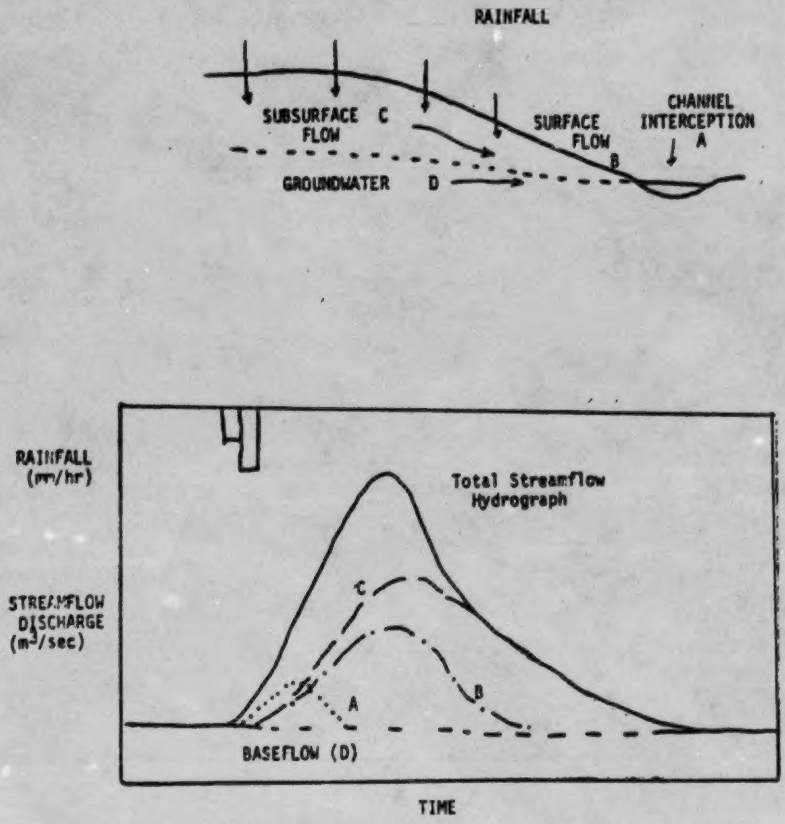
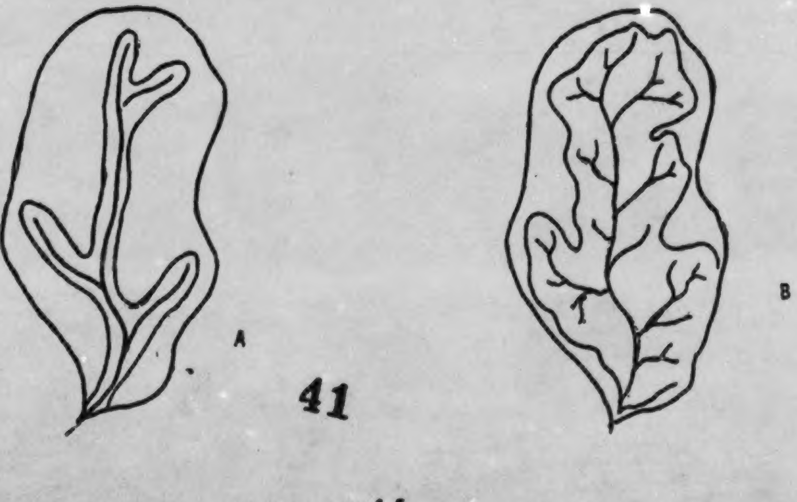

RAINFALL
SUBSURFACE FLOW C
SURFACE FLOW B
CHANNEL INTERCEPTION A
GROUNDWATER D
RAINFALL (mm/hr)
STREAMFLOW DISCHARGE (m^3/sec)
Total Streamflow Hydrograph
C
B
A
BASEFLOW (D)
TIME

Figure 9. Variable-source-area concept; cross-hatched area represents contributing areas early (A) and late (B) in a rainstorm. Note the channel expansion over time.



Measurement of Precipitation

John Thames

Purpose: to acquaint the participants with:

1. Factors affecting the accuracy of precipitation meaasurements
2. Methods of gauging precipitation
3. Techniques of estimating average precipitation for a watershed
4. Analyses of rainfall records.

Input (precipitation)

The measurement of precipitation is an integral part of most hydrologic projects. Information on precipitation — amount, intensity, type, frequency, duration — is essential to much of the research and to the development of operational programs in the management of watershed lands. Although a wide variety of gauges have been developed, the basic method of making measurements has remained unchanged since 1400, when rain gauges — similar to those now in use — were first used in Korea. The major problems have usually been to make point measurements accurately and to extrapolate point values to estimates for areas.

Types of Gauges (Point Measurements)

Three types of precipitation gauges are now in general use: (1) the standard gauge -- size varies with standards established in individual countries — (usually read after each storm event or at relatively short predetermined time intervals); (2) the storage gauge (manufactured in several sizes and read only periodically); and (3) the recording gauge (records rate of precipitation as well as depth).

It has been shown that over a 16-year period the difference in rainfall catch between a standard gauge and a weighing-recording gauge was less than 0.05 percent. Properly exposed, calibrated, and evaluated, the 8-in. diameter weighing rain gauge yields hourly precipitation values with standard error of about 0.01 in. so that reliability within 0.02 may be assumed.

Gauges with several different orifice diameters seem to measure rainfall with about the same degree of accuracy. It has been found that rain gauges with orifices 2 to 24 inches in diameter do not vary by more than 1 or 2 percent in accuracy of measurement.

Errors in Point Measurement of Precipitation

The effects of wind are due primarily to an increase in pressure on the windward side of the gauge, a decrease in pressure and a marked acceleration of wind over the top of the gauge, and eddy currents over and within the orifice. As wind speed normally increases with height, the higher the collector is placed above the ground the greater will be the error due to wind effect.

The catch of an unshielded 8-in. gauge, even when only moderately exposed to the wind, is about 5 percent less than the true precipitation.

Improving the Accuracy of Point Measurements

To correct the errors due to wind turbulence, several types of windshields have been developed. The most notable of these are the Nipher and Alter shields. Windshields are designed to divert the flow of air down and around the rain gauge to eliminate updraft in the region of the orifice, thus placing it in an undisturbed flow of air.

The relative effectiveness of the Alter and Nipher shields has been investigated on a total catch basis. The general consensus is that the Nipher shield was superior for reducing wind errors.

The pit gauge probably gives the most accurate measurements of rainfall at a point. When the rain gauge is placed in a pit with its orifice level with the land surface, any deleterious wind effects on the gauge are diminished. However, pit gauges are inadequate for snow measurement. And for extensive rain gauge networks, the increased accuracy may not warrant the additional cost of installing and maintaining pit gauges.

Selection of Raingauge Sites

Three general types of natural parameters which affect the variation in amounts of precipitation over an area are: (1) weather itself, in terms of area distribution of condensation processes and types of circulation of and within storms; (2) topoography of a scale large enough to affect the weather; (3) smaller scale terrain effects which influence the performance of the gauge. The selection of a gauge site, which is representative of the surrounding area, will be influenced primarily by factor (3).

Local anomalies in the rainfall pattern may be produced by small-scale topographic influences or by obstructions which distort the wind pattern in the immediate vicinity of the gauge. This distortion may make the particular gauge site nonrepresentative of the general region, introducing an error in the determination for the area. In regions of flat topography, this factor is usually of minor importance. In mountainous terrain, it may account for much of the variation in precipitation measurements. Variation in precipitation may be attributed in some cases to variations in the local exposure of gauge sites rather than in actual differences in the distribution of precipitation.

An ideal exposure would eliminate all turbulence and eddy currents near the gauge. Individual obstructions, whether a building or a tree, may set up serious eddy currents and, as a general rule, should not be closer to the gauge than twice (preferably four times) the height of the object above the gauge. When objects are numerous and uniform, such as in a forest opening, their height above the gauge should not exceed about twice their distance from the gauge.

At exposed sites, compensate for the lack of natural protection by shielding or by using pit gauges. The Nipher shield is recommended if the precipitation is primarily rain, the Alter shield if a substantial portion of the precipitation is snow.

Measurements for Areas

Fairly wide variations in precipitation exist in areas of level terrain as well as in those of considerable relief. Most of these variations are due to storm type, elevation, aspect, land slope, wind direction, and wind speed.

Assuming that individual records used are reliable, the accuracy of an estimate of area rainfall seems to depend primarily on the actual range of rainfall within the area, and on the number of records used. For a given number of stations the accuracy of the average is proportional to the range of variation between the amounts for the different stations.

The fairly wide variations in precipitation, due to storm type or terrain, point out the fallacy of taking the records of one station as representative or typical of large areas. It should also be kept in mind that the sampling area of a standard 8-in. rain gauge is only 8 x 10^{-6} acre in size.

How accurately a point rainfall measurement represents the mean rainfall for areas of varying sizes in the vicinity of the point observation is pertinent to the design of rain gauge networks and to the interpretation of data.

Number of Gauges Required

An example for locating rain gauges in agricultural watersheds ranging in size from 23 to 330 acres is given in Table 4. Considered here are both area distribution and site exposure requirements for areas with a continental type of climate, where heavy precipitation often occurs as a result of thunderstorms.

The use of random sammpling as a means of excluding bias in the selection of gauge sites and for estimating the number of gauges needed is suggested. Random sampling also lends itself to standardized statistical methods of analyses. However, in areas of dense brush or forest, this type of rainfall sampling may not be practical owing to the difficulty of obtaining adequate sampling sites.

Rainfall variability on a watershed for monthly, seasonal, or annual periods can be estimated at much lower operating cost by using a regular network which is read after each storm event. By reading storage gauges monthly or seasonally, the effects of storm types on variability may be lost, but systematic differences in precipitation between parts of the watersheds for these longer periods can be estimated.

Methods of Calculating Mean Watershed Precipitation

The mean depth of precipitation over a watershed is required in most hydrologic investigations. Several procedures are used in deriving this value. The three most common are the arithmetic, the Thiessen, and the isohyetal methods.

Arithmetic Method — A straight arithmetic average is the simplest of all methods for estimating the mean rainfall on a watershed. This method yields good estimates in level terrain if the gauges are numerous and uniformly distributed. Even in mountainous country with a dense rain gauge network, arithmetic averages will yield fairly accurate results if the orographic influences on precipitation are considered in the selection of gauge sites. However, if gauges are relatively few and irregularly spaced and precipitation over the area varies considerably, the arithmetic mean is likely to differ greatly from the results derived by other methods.

Thiessen Method — This method involves determination of an area of influence for each station. Polygons are formed from the perpendicular bisectors of lines joining nearby stations. The area of each polygon is determined and is used to weigh the rainfall amount of the station in the center of the polygon. The entire area within any polygon is nearer to the rainfall stations contained therein than to any other, and it is, therefore, assumed that the rainfall recorded at that station should apply to that area. The results are usually more accurate than the arithmetic average unless a large number of gauges are used. The Thiessen method allows for non-uniform distribution of gauges by providing the weighting factor for each gauge.

The method assumes linear variation of precipitation between stations and makes no attempt to allow for orographic influences.

Isohyetal Method — In the isohyetal method, station location and amounts are plotted on a suitable map, and contours of equal precipitation (isohyets) are drawn. The average depth is then determined by computing and dividing by the total area. Many investigators indicate this as theoretically the most accurate method of determining mean watershed precipitation. But it is also by far the most laborious.

The accuracy of the isohyetal method depends upon the skill of the analyst. An improper analysis may lead to serious error. If linear interpolation between stations is used, the results will be essentially the same as those obtained with the Thiessen method.

Summary

In evaluating the accuracy of precipitation measurements on watersheds, consideration must be given to errors due to (1) failure of the rain gauge to represent actual point rainfall and (2) extrapolation of point rainfall to area values.

The accuracy with which a gauge measures precipitation at a point is influenced by many factors, the most important of which is wind (exposure). Under exposed conditions, wind action on the gauge tends to reduce the catch. The precision of point rainfall measurements may be increased by using a Nipher windshield on the gauge or by placing the gauge in a pit with its orifice parallel to the slope of the ground. Tilted gauges have improved the catch at exposed mountain sites, especially when precipitation falls at large inclinations from the vertical. However, they are not recommended unless considerable study is made beforehand.

Fairly wide variations in precipitation have been shown to exist in areas of level terrain as well as those of considerable relief. Most of these variations are accounted for by storm type, elevation, aspect, land slope, wind direction, and wind speed. Enough gauges must be used to sample adequately the variations to obtain reliable estimates of area. The average difference between point and area mean rainfall increases as the storm size increases, and it decreases as sampling time increases. The relative variability tends to decrease as storm mean rainfall increases and as the totalizing period is increased. Standards of accuracy for area averages should be modified in inverse relation to the size and importance of storms to avoid using an impractically large number of rain gauges.

For areas of relatively flat terrain, a uniform distribution of gauges is best for determining amount and variability of precipitation. In mountainous areas, however, altitude and aspect as well as area must be fully sampled to derive accurate estimates of precipitation over a watershed.

The fairly wide variation in precipitation, owing to storm type or terrain, points out the fallacy of taking the records of one station as representative of large areas. Whether a gauge site is representative of an area can be determined only by sampling the immediate vicinity with several gauges to obtain a measure of existing variation. To calculate mean basin precipitation on watersheds having well-designed rain gauge networks, the Thiessen method is the most expedient to use.

References

International Symposium of Forest. 1965. Edited by W. E., Sopper and H. W. Lull. Pergamon Press.

Field Manual for Research in Agricultural Hydrology. 1961. Agriculture Handbook No. 224. A.R.S.— U.S.D.A.

Table 1. Approximate errors in precipitation measurement.
(from Kurtyka, 1953)

Factors	Percent Error
Evaporation	-1.0
Adhesion	-0.5
Color	-0.5
Inclination	-0.5
Splash	+1.0
Subtotal	-1.5
Exposure	-5.0 to -80.0

Table 2. Effect of gauge height on rainfall catch

Height above ground (cm)	2	4	6	8
Rainfall (mm)	105	103	102	101

100 500 2000

100 95 90

Table 3. Effect of shielding.

Wind velocity (m.p.h.)	Percent increase in shielded gauge catch	
	Rain	Snow
0–30	4	34
30–75	40	69
> 75	42	300

Table 4. Measurement of precipitation on experimental agricultural watersheds.

Size of drainage area (acres)	Minimum number of rainfall stations
0 to 30	1
30 to 100	2
100 to 200	3
200 to 500	1 per 100 acres
500 to 2500	1 per 250 acres
2500 to 5000	1 per square mile
over 5000	1 per each 3 square miles*

* This recommendation will often be impractical in watersheds of more than 20 square miles. For larger areas, strive for good distribution with as many rainfall stations as can be properly maintained and serviced.

Rain gauge chart.

Stream Flow Measurements — Stream Gauging

John Thames

Purpose

1. To define some of the principal terms used to describe the discharge from a watershed.

2. To acquaint the student with methods used for gauging stream flow.

Measuring Stream Flow

Stream flow data is perhaps the most important information needed by both the engineer and the water resource manager. Peak flow data are needed in planning for flood control or engineering structures (e.g., bridges, culverts, etc.). Minimum flow data are required for estimating the dependability of water supplies. Total runoff and its variation must be known for design purposes (e.g., investigation works, storage reservoir, etc.).

The stream hydrograph is a record of the discharge of a watershed as it changes with time. It provides a record that shows the integrated effects of the hydrologic processes which occur in a watershed and, therefore, the hydrologic condition of the watershed.

Analyses of single storm hydrographs (the reaction of a stream to a rainstorm event or period of snowmelt) can indicate the condition of a watershed and provide information on the effects of land use and management practices (see Fig. 1). Storm hydrographs can be separated into components of quick return flow (primarily surface runoff) and subsurface runoff (base flow and interflow).

The stage of water in a stream is readily measured at some point on a stream reach with a staff gauge or a clock-driven water level recorder. The problem is to convert a record of the stage of a stream to discharge or quantity of flow per unit of time. This is accomplished either by stream gauging or with pre-calibrated structures such as flumes or weirs constructed in the stream.

Stream gauging

In stream gauging, this requires the development of a rating curve or rating table which indicates the relationship between stream discharge and stream stage (see Fig. 2).

Discharge can be computed if the velocity and cross sectional area of the stream are known. The stage can be measured from a reference level (usually some point in the stream bed) to the surface of the water. When a sufficient number of stages and their associated discharges have been measured a rating curve can be constructed similar to the one shown in Fig. 2.

One of the simplest ways of measuring discharge is to observe how far some floating object tossed into the stream travels in a given length of time. A measurement of the cross sectional area of the stream should be made simultaneously; the two should then be multiplied together:

$$VA=Q$$

where V = the velocity in feet per second
A = the cross section in square feet
Q = the discharge in cubic feet per second.

However, a simple measurement such as this would not be very accurate, particularly for a large stream because velocity varies from point to point with depth and width over the cross section of a stream.

Ideally, the velocity profile of a longitudinal section of a stream would appear as shown in Fig. 3.

The velocity at the surface is greater than the mean velocity of the stream; thus, a reduction factor is needed if the velocity is measured at the surface. Generally it is assumed to be about 85 percent.

From the preceding, the velocity profile of a stream would appear as shown in Fig. 4. However, because of the roughness, configuration, and turbulence of natural streams such ideal profiles would seldom exist. Since the discharge of a stream is the product of its cross sectional area and the mean velocity, accurate measurements of both these quantities are needed to construct an accurate rating curve.

If the cross section of a stream is divided into finite vertical sections, the velocity profile can be estimated by measuring individually the mean velocity of each section. The area of each section can be determined and the average discharge of the entire stream is then computed as the sum of the product of area and velocity of each section as follows:

$$\sum_{1}^{n} A_i V_i$$

where n = the number of sections.

The greater the number of sections, the closer the approximation. However, for practical purposes, 10 sections are usually sufficient under ideal conditions, but 20 are commonly used. The actual number then depends upon the stream's channel and the rate of change in the stage. The following rules should be observed: (1) depth and velocity should not vary greatly between verticals, and (2) the measurements should be completed before the stage changes too much (a 0.5 foot change is too much for most cases).

There are two ways of approximating areas. They are: (1) the midsection method where each vertical is considered the midpoint of a rectangular subsection extending halfway to the midsection of the other vertical, and (2) the mean section method where each section is considered a trapezoid. The midsection method is most commonly used (Fig. 5).

Velocity and depth of verticals can be taken by wading into the stream, from cable car, boat or bridge. Velocity is usually measured with a current meter. There are several ways of performing a velocity measurement. Consider again the longitudinal velocity profile (Fig. 3). For depths greater than 1.5 feet, two measurements are made for each section at 20 and 80 percent of the total depth. For example, if the depth of water at a station is 1.8 feet, the current meter is set at .2 x 1.8 = .36 foot and at .8 x 1.8 feet = 1.44 feet below the water surface. For depths less than 1.5

feet the current meter is set at .6 of the depth. For shallow streams less than .5 foot, a pygmy meter is used which is simply a smaller version of a current meter.

The most critical aspect of stream gauging is the selection of a control, that is, the point on the stream for which a rating curve is to be developed. Thus many sections of the channel which act as controls during low stages will have almost no effect on the water surface at points upstream.

Except in places where a rock outcrop creates either a waterfall or a rapids with considerable drop, a longitudinal river profile is a practical necessity in determining the location of the various controls in any given length of stream channel. The best control is the one that is the most nearly permanent and that functions as a control throughout all stages of the river.

There must be of course a nearby gauging station equipped with a water stage recorder that has hydraulic connections with the water in the stream.

Figure 1. Idealized hydrograph.

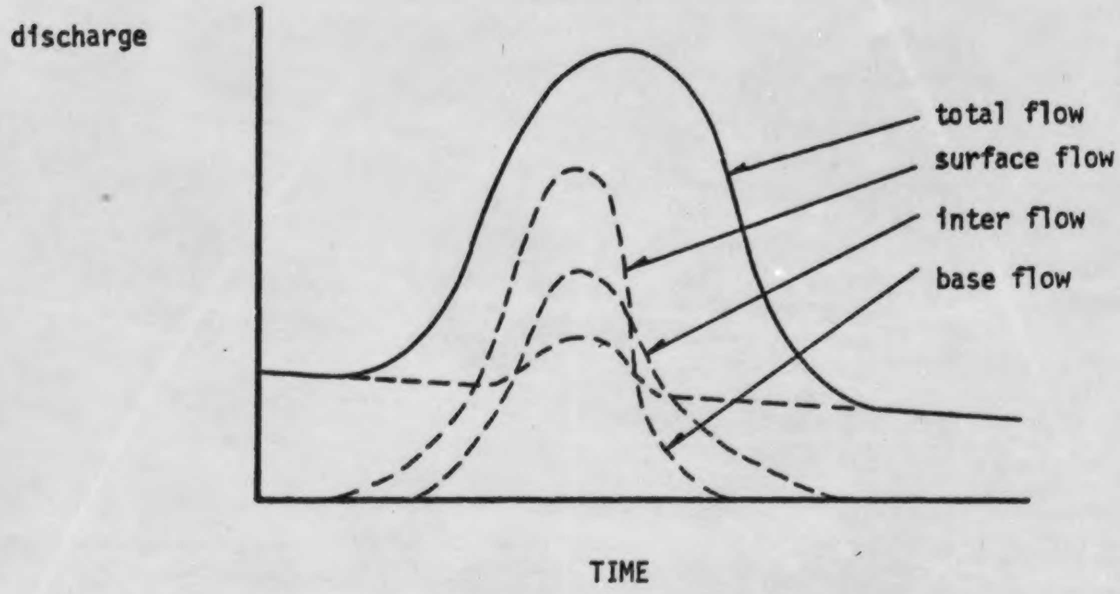


Figure 2. Rating curva.

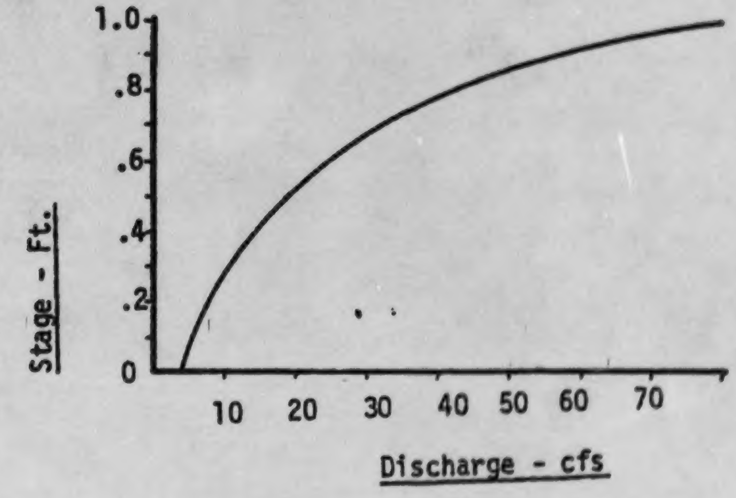


Figure 3. Longitudinal section of a stream.

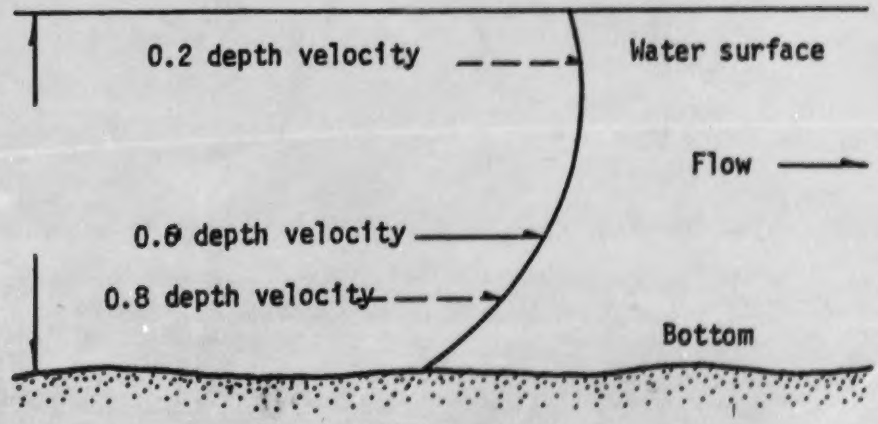

0.2 depth velocity
Water surface
Flow
0.6 depth velocity
0.8 depth velocity
Bottom

Figure 4. Vertical velocity profile of a stream.

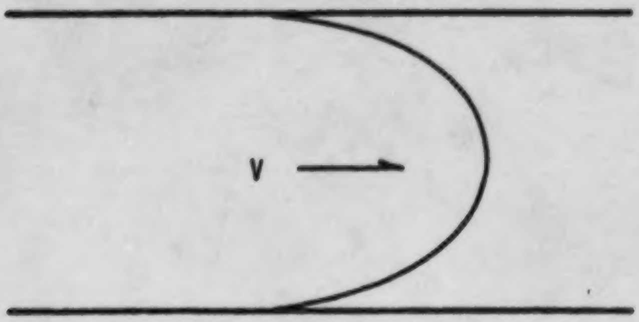
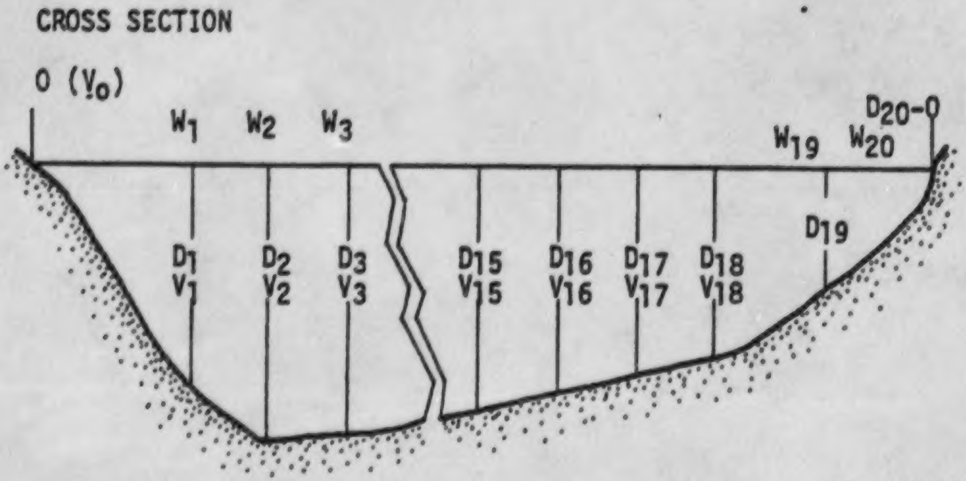


Figure 5. Measurements needed to record channel cross section and velocity.


CROSS SECTION
0 (V_0)
W_1
W_2
W_3
W_{19}
W_{20}
D_{20}-0
D_1 V_1
D_2 V_2
D_3 V_3
D_{15} V_{15}
D_{16} V_{16}
D_{17} V_{17}
D_{18} V_{18}
D_{19}

$$Q = \frac{W_1 + W_2}{2} V_1 D_1 + \frac{W_2 + W_3}{2} V_2 D_2 \text{ etc.}$$

W = width, feet
D = depth, feet
V = velocity, feet per second
Q = discharge, cubic feet per second

Precalibrated Structures for Stream Flow Measurement

Purpose

1. To acquaint the participant with the common structural devices used to measure streamflow.
2. To provide design and construction criteria for flumes and weirs.
3. To give the student practice in analyzing stream flow records.

Weirs and Flumes

On small watersheds, particularly experimental watersheds, precalibrated structures are often used because of their convenience and accuracy.

Small watersheds include those of a few to about 1,500 acres. Such watersheds are small enough so that construction of an artificial control is not impractical. On larger streams, gauging is usually done by using natural controls as discussed in the preceding section.

The most common types of precalibrated structures are weirs and flumes. The various objectives for which stream-gauging stations have been built have resulted in many different designs for weirs and flumes. Weirs are often preferred for gauging small watersheds particularly those with perennial flows. Where heavy sediment-laden flows are common, flumes are often more convenient. A flume is a stabilized channel (without an impoundment) with access to a stilling well. Flumes also must be used where the gradient of the stream is particularly low.

Weirs or flumes can be constructed of a great many materials. Concrete, because of its strength and permanence, probably is used the most. Treated wood, concrete blocks, metal, and many other materials are also used. The notch of a weir is often a steel blade set into concrete, and flumes are often lined with steel for permanence.

Weirs

As used here, weir includes all components of a stream-gauging station that incorporates a notch control (Figures 1 and 2). An impoundment of water (the weir basin) is formed upstream from the wall or dam containing the notch. A stilling well with water-level recorder is connected to the weir basin. A gaugehouse or some other type of shelter is provided to protect the recorder.

The cutoff wall or dam is used to divert through the notch all water (above or below the streambed) moving down the channel. Where possible, the cutoff wall is tied into bedrock or other impermeable material so that no water can flow under or around it. But where leakage is apt to occur, the weir basin is sometimes constructed as a watertight box.

The edge or surface over which the water flows is called the crest. Weirs can be either sharp crested or broad crested. A sharp-crested weir has a blade with a sharp upstream edge so that the passing water touches only a thin edge and springs clear of the rest of the crest.

A broad-crested weir has a flat or broad surface over which the discharge flows. Broad-crested weirs are generally used where sensitivity to low flows is not critical and where sharp crests would be dulled or damaged by sediment or debris.

The sheet of water flowing over the weir is the nappe. The weir has free discharge if the nappe discharges into the air: air circulates freely on all sides of the flow issuing from the weir notch.

As the nappe flows through the notch, the velocity of flow increases and the nappe cross section is reduced or contracted. The contraction is affected by the shape of the notch and basin characteristics immediately upstream from the notch.

Where the depth of water from the crest to the basin flow is less than 2.5 times the head of water over the crest, the crest contraction of the nappe is partially suppressed. Velocity of approach will increase, and actual discharge will be greater than that shown by the normally used formulas and tables (Fig. 1).

If the basin is the same width as the crest, the weir has its end contractions suppressed. For complete end contractions, the distance from the edge of the notch to the side of the weir basin or channel should be at least 2.5 times the head being measured. A narrower weir basin or channel results in increased velocity of approach and increased flow for a given head.

For best results, the velocity of approach should be held to a maximum of 0.5 foot per second. Where velocities of approach are appreciable, the discharge should be corrected.

Water discharging over the crest of a weir drops slightly in elevation immediately upstream from the crest. This decrease is caused by the water's acceleration in velocity as it approaches the crest. Such a drop is called surface contraction or drop-down. In sharp-crested weirs, the effect of this surface contraction extends upstream from the crest a distance twice the head of water flowing over the crest. Therefore, the intake to the stilling well should be located upstream from the crest a distance equal to or greater than twice the head of the maximum anticipated flow (Fig. 2). Fully contracted weirs are generally preferred in research.

The rectangular weir has vertical sides and horizontal crest. Its major advantage is its capacity to handle high flows. However, the rectangular weir does not provide for precise measurement of the low flows of small experimental watersheds — a small increase in head will give only a slightly increased discharge.

The trapezoidal weir is similar to the rectangular weir. Its sides, of course, are sloped from the vertical. It has a smaller capacity than a rectangular weir of the same crest length; the discharge is approximately the sum of discharges from the rectangular and triangular sections.

Sharp-crested V-notch or triangular weirs are often used where accurate measurements of low flows are important. The V-notch weir may have a rectangular section above to accommodate infrequent high flows.

The two most common sharp-crested V-notch weirs are the 90° notch and the 120° notch, with metal blades ground to a sharp edge and built into a concrete cutoff wall. The 90° type gives greater sensitivity at low flows; the 120° type covers a wider range of flows. V-notch weirs are usually constructed to accommodate heads up to 2 feet; however, both in the United States and elsewhere V-notch weirs capable of handling gauge heights in excess of 2 feet are in use (see Appendix A).

Broad-crested triangular weirs with 2:1, 3:1, and 5:1 side slopes (with notches approximately 127°, 143°, and 157°, respectively) were developed and rated by the Soil Conservation Service for measuring flows up to about 1,000 cfs. The shape and thickness of the crest permits comparatively free passage of debris and minimizes the effect on the stage-discharge relationship of small irregularities of the crest and of trash temporarily lodged on the crest. A reasonably straight and practically level channel for 50 feet above the weir, with the notch 6 inches above the bottom of the approach channel, is essential for accuracy (see Appendix B).

Flume

A flume is an artificial open channel built to contain flow within a designed cross-section and length. The types of flumes that have been used on small watersheds are described here.

HS, H, and HL flumes developed and rated by the Soil Conservation Service have converging vertical sidewalls cut back on a slope at the outlet to give them a trapezoidal projection. These have been used largely to measure intermittent runoff. Maximum depths of waterflow are 1 foot for the HS type, 4.5 feet for the H type, and 4 feet for the HL type. Maximum flows are 0.8, 84, and 117 cfs, respectively. These flumes are in use at many Agricultural Research Service installations and a number of other locations (See Appendix A).

The Venturi flume (Fig. 3) has a gradually contracting section leading to a constricted throat and an expanding section immediately downstream. The floor of the Venturi flume is the same grade as the stream channel, whereas that of the Parshall flume (described below) is depressed in the throat section. Stilling wells for measuring the head are at the entrance and at the throat; the difference in head at the two wells is related to discharge. Venturi flumes are rectangular, trapezoidal, triangular, or any other regular shape. They are widely used in measurement of irrigation water.

The Parshall flume, a modification of the Venturi flume, measures water in open conduits and is widely used, especially for measuring irrigation water. It consists essentially of a contracting inlet, a parallel-sided throat, and an expanding outlet, all of which have vertical sidewalls. It can measure flows under submerged conditions. Two water-level recorders are used when measuring submerged flow, one in the sidewall of the contracting inlet and the other slightly upstream from the lowest point of the flow in the throat. When measuring free flow, only the upper measuring point is used.

The San Dimas flume (Fig. 4) was designed on the San Dimas Experimental Forest of the U.S. Forest Service to measure debris-laden flows in mountain streams. It is rectangular and has a sloping floor (3 percent gradient) that functions as a broad-crested weir except that the contraction is from the sides rather than the bottom; therefore, there is no barrier to cause sediment depositon. Depth measurements are made in the parallel-walled section at about the midpoint. Rapid flow keeps the flume scoured clean.

The types of weirs and flumes that have been discussed are those most used in research. In some cases, structures have been built to incorporate features of more than one type — for example, a 90° V-notch recently built into a Trenton-type weir at the Pennsyvania State University. When a wide range in flow or sediment load is anticipated, it may be advantageous to install more than one device at the same site.

Summary

The type of flume or weir to be used depends upon several factors: maximum and minimum flows; accuracy needed in determining total discharge, high flows, and low flows; amount of sediment or debris that is expected, and whether it is suspended or bedload; channel gradient; channel cross-section; underlying material; accessibility of site; financial limitations; and length of study.

Maximum and minimum flows likely to be encountered must be estimated before construction. Such estimates can be made from observation of high and low flows and high watermarks and from information given by local residents, or they might be based on the area of the watershed and records from other gauging stations in the region. Maximum expected flood peaks can also be estimated from rainfall, soil, and cover data, using a method developed by the U.S. Soil Conservation Service. Assistance should be sought from the U.S. Geoological Survey and U.S. Soil Conservation Service, if this approach is needed.

The maximum and minimum flow to be measured at any degree of precision depend upon the objectives of the study and the extremes that might occur. In some cases, a gauge will be adequate if it will measure, with acceptable accuracy, 80 to 90 percent of the flow. These limits exclude extreme peaks and very low flows. However, the structure must be strong enough to withstand the highest flow expected.

Once maximum and minimum estimates are made, reference to rating tables for various structures or to formulas for competing flow will show the types and sizes of installations that can be used. Maximum and minimum discharges for several types of weirs and flumes are given in Table 1. Rating tables will also show the relationship between the increase in discharge and the corresponding rise in head at various stage heights. This association indicates the sensitivty of the gauging station at different levels of discharge.

Rating can be simplified by choosing a design for which a state-discharge relationship has been determined in the laboratory. After construction, the laboratory rating should be checked at various gauge heights by direct measurement with current meter, velocity head rod, or another instrument for determining velocity, or by volumetric measurements.

Where excessive amounts of suspended sediment, bedload, and floating debris are encountered, flumes are preferable. Weirs would be unsatisfactory because the basin would trap this material, which would alter the weir rating, and debris would clog the crest of the weir, giving grossly inaccurate measurements. Broad-crested weirs are often used on agricultural watersheds where grass and other debris would lodge on a sharp-crested weir and invalidate the rating curve.

The gradient of the stream channel may affect choice of design. If the gradient is too low, it may be impossible to install a weir that will meet the requirements of a standard rating (depth of water below crest equal to at least 2.5 times the maximum head to be measured). A control with less evaluation may have to be built, and the station will then have to be rated by current meter or other means.

The channel cross-section and streambanks may dictate design. Under some conditions, a cutoff wall high enough to satisfy rating requirements would have to be of considerable length to tie into solid material at the sides. The cost of such a wall might rule out this type of installation.

Underlying marterial must be considered. If permeability is a problem, either a watertight-box weir design, which can support an artificial head of water, or a flume will be necessary.

With weirs, sharp crests give greater accuracy than broad crests. Blades of sharp-crested weirs are constructed of angle iron or steelplate, ground to a sharp edge or to a flat edge one-sixteenth inch wide, and set into concrete cutoff walls or dams. Blades may be dented, bent, rusted, and clogged with debris. In many locations they must be screened to prevent clogging, and care should be exercised when working near them; some maintenance, such as annual painting, is required.

Flumes are often satisfactory where weirs are impracticable. They can handle debris-laden flows better; even so, such flows may be difficult to measure. With flumes, velocity of approach is less of a problem than with weirs. There is less loss in head with flumes than with weirs; thus, they can be used in channels with low gradients. This is one of the main reasons why flumes are used in measurement of water for irrigation. And flumes, requiring no excavation for ponding, may be easier and cheaper to install.

Details of construction of an H-flume and V-notch and sharp-crested weirs are given in Appendixes A and B. Methods for computing rainfall intensity from recording raingauge charts and for computing runoff from a stage recorder chart are given in Appendix D.

Literature

Much of this section was taken directly from the following publications:

International Symposium of Forest. 1965. Edited by W. E. Sopper and H. W. Lull. Pergamon Press.

Field Manual for Research in Agricultural Hydrology. 1961 Agriculture Handbook No. 224, A.R.S.—U.S.D.A.

Stream-gauging Stations for Research on Small Watersheds. 1964. K. G. Reinhart and R. S. Pierce.

Table 1.

Maximum and minimum discharges for several types of weirs and flumes in cubic feet per second (approximate).

WEIRS

Type	Minimum	Maximum
Sharp-crested weirs:		
2 feet high, 90° V-notch	<0.001	14
2 feet high, 120° V-notch	<.001	24
2 feet high, 6 feet wide rectangular	[1].24	56
2.75 feet high, 8 feet wide Cipolletti	[1].30	123
4 feet high, 12 feet wide Cipolletti	[1].46	323
Broad-crested weirs:		
Triangular 2:1 side slopes	[22].017	[3]510
Triangular 3:1 side slopes	[2].025	[3]803
Triangular 5:1 side slopes	[2].037	[3]1,440
2 feet high Columbus deep notch	.026	62

FLUMES

HS type:		
0.4 foot high	[1]0.001	0.1
1.0 foot high	[1].002	.8
H type:		
1.0 foot high	[1].004	2
2.0 feet high	[1].007	11
4.5 feet high	[1].015	84
HL type:		
4.0 feet high	[1].03	117
San Dimas:		
1 foot wide	.1	6
3 feet wide	2	77
6 feet wide	10	318
10 feet wide	36	1,000
Trapezoidal:		
1-foot-wide throat, 4 feet high, 30° side slopes.	[1].15	350
Parshall:		
1 foot wide, 2.5 feet high	.4	16
2 feet wide, 2.5 feet high	.7	33
4 feet wide, 2.5 feet high	1.3	68
8 feet wide, 2.5 feet high.	4.6	140

[1] Flow at 0.05-foot head.

[2] Flow at 0.1-foot head.

[3] Flow at 6-foot head with cross-sectional area of 300 square feet in the channel of approach 10 feet upstream from center of crest.

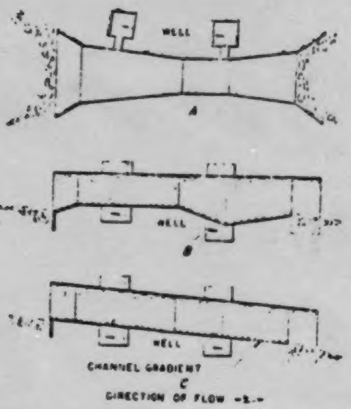

WELL
A
WELL
B
WELL
CHANNEL GRADIENT
C
DIRECTION OF FLOW

Fig. 3. Schematic diagram of Venturi flume, which requires measurement of stage at two points. Flume is same grade as stream channel. A, Plan view of Venturi flume; B, cross-section of Venturi flume.

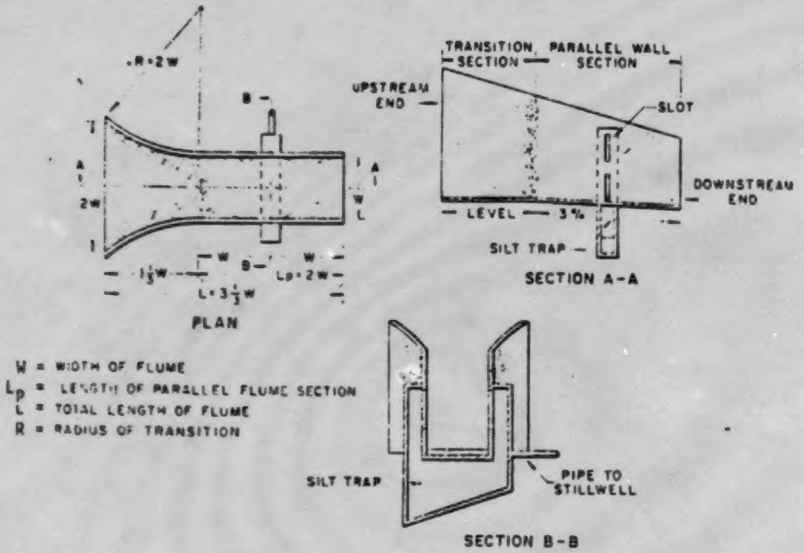

R = 2W
B
A
2W
A
W
L
1⅓W
W
B
W
Lp = 2W
L = 3⅓W
PLAN
W = WIDTH OF FLUME
Lp = LENGTH OF PARALLEL FLUME SECTION
L = TOTAL LENGTH OF FLUME
R = RADIUS OF TRANSITION
TRANSITION SECTION
PARALLEL WALL SECTION
UPSTREAM END
SLOT
DOWNSTREAM END
LEVEL
3%
SILT TRAP
SECTION A-A
SILT TRAP
PIPE TO STILLWELL
SECTION B-B

Fig. 4. Generalized drawing of San Dimas flume. This design has been used for flumes with widths of 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, and 10.0 feet.

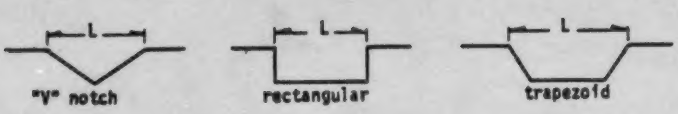
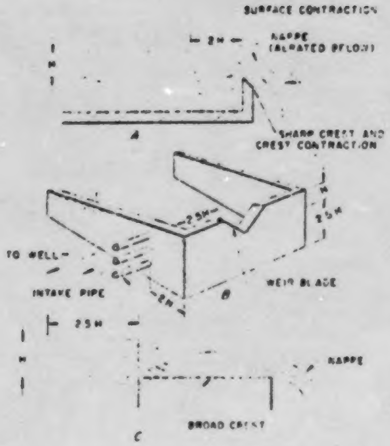

L
L
L
"V" notch
rectangular
trapezoid

Figure 1: Types of notches.


SURFACE CONTRACTION
2H
NAPPE (AERATED FLOW)
H
A
SHARP CREST AND CREST CONTRACTION
H
2.5H
2.5H
TO WELL
INTAKE PIPE
2H
B
WEIR BLADE
2.5H
H
NAPPE
BROAD CREST
C

Schematic diagrams of general hydraulic relationships for weirs. A, Flow characteristics over a sharp-crested weir; H is the depth of water producing the discharge; B, minimum requirements for proper discharge when H equals greatest expected depth for a sharp-crested V-notch weir with end and crest contractions; C, flow characteristics over a broad-crested weir of rectangular cross-section.

Figure 2.

Stream Flow Estimations — Simple Field Methods

John Thames

Purpose: To acquaint the participant with simple field methods of estimating stream discharge.

Flood flows and high peak flows are often of primary interest, particularly in determining downstream effects of land use, and for the design of engineering structures. Although it is rare for a field survey to coincide with a peak flow event, a measurement at any stage of flow can be very useful.

Surface floats are the simplest method of measuring the velocity of a stream and thereby estimating the volume of streamflow. A float is thrown into the center of the stream and the time it takes to travel a measured distance of stream reach is observed. Velocity is calculated as:

$$V = L/t$$

where V = velocity
L = length of stream reach, and
t = time

The volume of flow (discharge) is determined by

$$Q = A V$$

where Q = discharge in volume per unit of time and
A = cross-section at the mid-point of the stream reach.

The cross-section area of the stream is best determined by summing a series of cross-section segments across the channel as shown in the section on stream gauging. The accuracy of surface floats is rather poor, since they only indicate the velocity at the water surface and also can be influenced by the wind. The mean velocity of non-turbulent streams is generally about 0.85 x the surface velocity, so a correction factor should be applied. Accuracy can be improved, particularly for deep, slow flows, by using a cannister or rod float, so as to avoid wind effects. These can be improvised from materials at hand and are designed to float with their bulk below the water surface. Where it is difficult to recover floats, it may be better to release a series of surface floats across the stream, timing the velocity of each and letting them represent cross-section segments. Water discharge is then calculated as described in the section on stream gauging.

Empirical Estimations of Stream Flow

It must be emphasized that estimates, no matter how sophisticated, are never as good as direct measurements. However, in many developing countries stream gauging networks are few or data may be completely lacking. An estimation of streamflow, no matter how rough, is often essential for appraising the condition of catchments. Most often, a main interest is in flood flows. Of course, reasonable estimates can often be made by extrapolating information from a similar basin. However, this must be done cautiously and by an experienced individual.

Flow equations

Several empirical methods are available. Two in common use for estimating stream discharge at known stages (depths) of flow are the Manning and the Chezy equations.

The Manning Equation is:

$$V = 1/n \; R^{2/3} \; S^{2/3} \qquad (1)$$

where V = the average velocity in the stream cross-section in meters per second,
R = the hydraulic radius in meters, and R = A/P (i.e., cross-section area of flow divided by wetted perimeter)
S = the water surface slope in meters per meter, or hf/L, where hf = friction head loss or fall per reach of stream L,
n = a roughness coefficient.

The Chezy Equation is:

$$V = C \sqrt{RS} \qquad (2)$$

where C = the Chezy roughness coefficient.

Equations (1) and (2) are similar, and the relationship between the roughness coefficients is:

$$C = 1.81/n \; R^{1/6} \text{ (metric)} \qquad \text{or}$$

$$C = 1.5/n \; R^{1/6} \text{ (English)}$$

The equations are used in similar fashion: the hydraulic radius and water surface slope are obtained from cross-section and bed slope data in the field (Figure 1). The roughness coefficient is estimated from Table 1 and the average discharge Q is calculated by multiplying the velocity times the cross-section area (A in Figure 1). Since the Chezy and Manning equations are related by equation (3), it is only necessary to consider one of the coefficients (Gray 1970).

In practice, since the interest is in some previous peak flow, high-water marks must be located to estimate the depth of flow. Sometimes this can be obtained by measuring the height of debris caught up along the stream channel (Figure 2) or by interviews with local inhabitants. This should be obtained for a reach of channel where the cross-section of the flow of interest can be measured with reasonable accuracy. The slope of the water surface can be approximated by the slope of the stream channel along the reach. The wetted perimeter can be measured by laying a tape on the channel bottom and sides between the high water marks. The cross-section area should be measured by summing several segments.

Frequently, it is not possible to obtain the measurements needed for equations 1 or 2, particularly where there is no well-defined channel or where the flow spreads over an adjacent plain or where evidence of high flows cannot be obtained from interviews. In these cases, it is necessary to resort to empirical methods such as the SCS method described in another section. There are also several simpler methods that can be used for small catchments which require easily obtained measurements. The Rational Method is one of the most common.

Table 1: Values of roughness coefficient "n"

Type of channel and description	Minimum	Normal	Maximum
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
2. Bottom: Cobbles with large boulders	0.040	0.050	0.070
B-2 Flood plains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense willows, summer, straight	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
B-3 Major streams (top width at flood stage >100 ft). The n value is less than that for minor streams of similar description, because banks offer less effective resistance			
a. Regular section with no boulders or brush	0.025	...	0.060
b. Irregular and rough section	0.035	...	0.100

Type of channel and description	Minimum	Normal	Maximum
A. Excavated or Dredged			
a. Earth, straight and uniform			
1. Clean, recently completed	0.016	0.018	0.020
2. Clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.030
4. With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.028	0.030	0.035
5. Stony bottom and weedy banks	0.025	0.035	0.040
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. No vegetation	0.025	0.028	0.033
2. Light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. Smooth and uniform	0.025	0.035	0.040
2. Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	0.050	0.080	0.120
2. Clean bottom, brush on sides	0.040	0.050	0.080
3. Same, highest stage of flow	0.045	0.070	0.110
4. Dense brush, high stage	0.080	0.100	0.140
B. Natural Streams			
B-1. Minor streams (top width at flood stage 100 ft)			
a. Streams on plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4, but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080

Rational Method

Often, for purposes of designing small dams, water diversions or culverts, the peak flow estimation most generally employed for small watersheds is the so-called Rational Method. It is summarized in the equation:

$$q_p = C\ i\ A/36 \qquad (3)$$

where q_p = peak rate of flow in cubic meters per second
c = coefficient of runoff,
i = design rainfall intensity in centimeters per hour for a given frequency and a duration equal to the time of concentration of the basin
A = area in hectares

Values for the coefficient of runoff are given in Table 2. The time of concentration, T_c, is the time it takes for water to travel from the most distant point on the watershed to the watershed outlet. An equation for estimating this watershed characteristic is:

$$T_c = L^{1.15}/15\ H^{0.38} \qquad (4)$$

where T_c = time of concentration in hours
L = length of the watershed along the main stream from the outlet to the most distant ridge in kilometers, and
H = the difference in elevation between the watershed outlet and the most distant ridge in kilometers.

In areas where rainfall records are lacking, the time of concentration can be calculated to arrive at the duration of the design storm. Intensity can then be estimated either from what local information is available or obtained from adjacent areas where there are data.

Values of C for Rational Formula 2

Soil type	Watershed cover		
	Cultivated	Pasture	Woodlands
With above-average infiltration rates; usually sandy or gravelly	0.20	0.15	0.10
With average infiltration rates; no clay pans; loams and similar soils	0.40	0.35	0.30
With below-average infiltration rates; heavy clay soils or soils with a clay pan near the surface; shallow soils above impervious rock	0.50	0.45	0.40

Other Information

For more information on runoff evaluation and on instrumentation, the reader may wish to request lists of available studies and reports in hydrology from the International Hydrological Programme, UNESCO, Place de Fontency, 75 Paris 7eme, France, particularly their book "Representative and Experimental Basis." WMO also has a Series of "Technical Notes" on hydrology, produced by the working group of the Commission for Hydrology, World Meteorological Organization, CH 1211, Geneva 20, Switzerland. They also produce a "Guide to hydrological practices."

The FAO Land and Water Development Division issues hydrological reports in its "Irrigation and Drainage Paper" series, FAO, via delle Terme di Caracalla, Rome.

Much useful information also is available from "Technical Bulletins" released by the Inland Waters Branch, Department of the Environment, Ottawa, Canada. The U.S. Geological Survey has a series "Techniques of water-resource investigations of the U.S.G.S.," available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Their series of "Water supply papers" also is useful.

In the French language, a hydrological series is offered by the Office de la Recherche Scientifique et Technique Outre-mer, 19, rue Eugene Carriere, Paris, 18eme.

A good summary of hydrology produced in conjunction with the International Hydrological Decade (UNESCO) is "Handbook on the principles of hydrology" (D. M. Gray, ed.) by the National Research Council of Canada, available from Water Information Center, Inc., Water Research Building, Manhasset Isle, Port Washington, N.Y. 11050, U.S.A. A useful reference also is the "Handbook of applied hydrology" by Chow (ed.), Mc-Graw-Hill Book Company, N.Y. Of course many individual texts are available in various specialized topics of the field of hydrology.

References

Chow, Ven Te. Handbook of Applied Hydrology. McGraw-Hill Book Co., New York. 1964

Gray, D. M. (ed.). Handbook on the Principles of Hydrology. National Research Council of Canada. 1970.

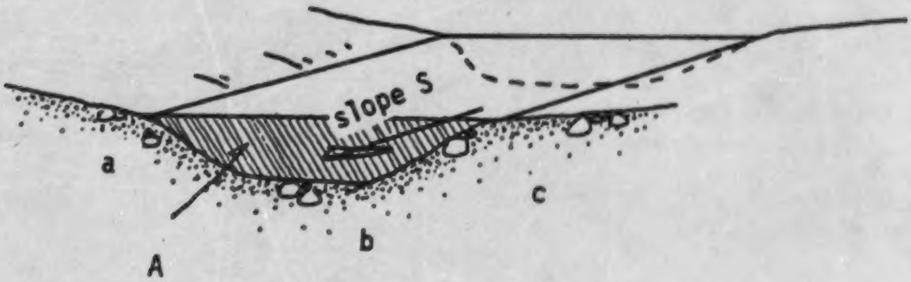

slope S
a
c
b
A

Figure 1. Stream channel section showing slope or gradient of streambed, wetted perimeter P (which is line a-b-c) and cross-section area A. R = A/P.

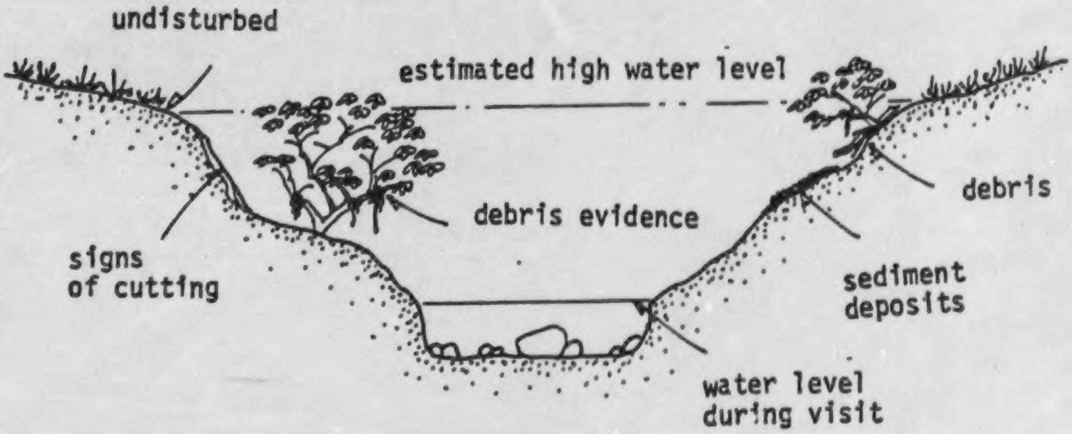

undisturbed
estimated high water level
debris
debris evidence
signs of cutting
sediment deposits
water level during visit

Figure 2: Loooking for evidence of high water level in the field.

Stream Flow Estimation: SCS Method

John Thames

Introduction

In many areas of the world there is little or no information pertaining to the quantity and timing of runoff from watershed lands. This presentation discusses the U.S. Soil Conservation Service method for estimating water and sediment yields from small ungaged watersheds. While its initial use was intended for the more humid regions, this procedure is now also used in arid regions. Although runoff data for small watersheds is generally lacking, information on precipitation is generally available for the site in question or can be obtained by extrapolation from areas where data is known. Some means is needed, therefore, to transform precipitation into runoff volume and peak flow rates.

Storm runoff volume

For ungaged watersheds, the Soil Conservation Service (SCS) uses the following basic rainfall-runoff equation for estimating the runoff volume from a given storm:

$$Q = (P - 0.2S)^2 / P + 0.8S$$

where Q = storm runoff, in mm
P = storm rainfall, in mm
S = a watershed factor which reflects the infiltration characteristics of the area under consideration, also expressed in mm.

A watershed index W, sometimes called a runoff curve number is related to S by the equation

$$W = 1{,}000/10 + S$$

The watershed index depends on soil type, the general hydrologic condition of the area, the nature and extent of cover and the antecedent moisture condition at the start of the storm period which produces runoff.

Soil types are classified into four groups, the details of which are given in Table 1.

Table 1. Soil Groups for Estimation of Watershed Index W

Soil Group	Description of soil characteristics
A	Soil having very low runoff potential. For example, deep sands with vey little silt or clay.
B	Light soils and/or well structured soils having above-average infiltration when thoroughly wetted. For example, light sandy loams, silty loams.
C	Medium soils and shallow soils having below- average infiltration when thoroughly wetted. For example, clay loams.
D	Soils having high runoff potential. For example, heavy soils, particularly clays of high swelling capacity, and very shallow soils underlain by dense clay horizons.

Three antecedent moisture conditions are allowed for, depending on the amount of rainfall received 5 days prior to the runoff. Details of these conditions are given in Table 2.

Table 2. Antecedent Moisture Conditions for Estimation of Watershed Index W

Antecedent Moisture Condition (AMC)	Rain in previous 5 days
I	< 15 mm
II	15 to 40 mm
III	> 40 mm

Figure 1, which is more applicable to semiarid regions,and Table 3 both give values for the watershed index for various soil-hydrologic-cover combinations, assuming antecedent moisture condition II. For other antecedent moisture conditions, the value of W obtained from Table 3 must be adjusted as shown in Table 4.

The meanings of the terms listed in Table 3 under the heading "Hydrologic Condition" are as follows:

a. Native pastures: Pasture in poor condition is sparse, heavily grazed pasture with less than half the total watershed area under plant cover. Pasture in fair condition is moderately grazed and with between half and three-quarters of the catchment under plant cover. Pasture in good condition is lightly grazed and with more than three-quarters of the catchmen area under plant cover.

b. Timbered areas: Poor areas are sparsely timbered and heavily grazed with no undergrowth. Fair areas are moderately grazed, with some undergrowth. Good areas are densely timbered and ungrazed, with considerale undergrowth.

c. Improved permanent pastures: Densely sown permanent legume pastures with proper grazing management are said to be in good hydrologic condition.

d. Rotation pastures: Dense, moderately grazed pasturs used as part of a well-planned, crop-pasture-fallow rotation are considered to be in good hydrologic condition. Sparse, overgrazed or "opportunity" pastures are considered to be in poor condition.

e. Crops: Good hydrologic condition refers to crops which form part of a well-planned and managed crop, pasture, fallow rotation. Poor hydrologic condition refers to crops managed according to a simple crop fallow rotation.

Peak flow rate

With the aid of Figure 2, a synthetic traingular hydrograph of storm runoff is developed which can be used to derive the estimated peak flow rate. The general equation is:

$$q_p = KAQ/T_p$$

where q_p = peak runoff rate in cfs
A = watershed area in km
Q = storm runoff volume in mm
T_p = time in hours from start of runoff to peak rate
K = is a constant dependent on shape of hydrograph. A value of $K = 484$ is frequently assumed.

Time to peak, T_p , is estimated from a consideration of both rainfall and watershed characteristics. A relationship often used is:

$$T_p = .5D + .6T_c$$

where D = duration of excess rainfall in hours (for convective storms, this can be equal to the duration of rainfall).

T_c = time of concentration in hours, which is estimated from the following equation:

$$T_c = .0078\, L^{.77}\, S^{-.385}$$

where L = length of the watershed along the main stream from the outlet to most distant ridge in km.

S = average slope of the main stream, a dimensionless ration of difference in elevation between outlet and most remote point to length of watershed L.

For most cases, the constant K has a value of 0.75 if the units are similar for both sides of the peak flow equation.

Literature

Flaxman E. M. 1972. Predicting sediment yield in western United States. Journal Hydraulics Div. ASCE 98 (HY 12): 2073-2085.

Fogel, M. M. 1969. The effect of storm variability on runoff from small semi-arid watersheds. Transactions ASAE 12(6): 808-812.

Kent, K. M. 1968. A method for estimating volume and rate of runoff in small watersheds. USDA SCS-TP-149. 40 pp.

Soil Conservation Service. 1972. National Engineering Handbook. Section 4 Hydrology. U.S. Department of Agriculture. Washington, D.C.

Williams, J. R. and R. W. Hann, Jr. 1973. Hymo: Problem-oriented computer language for hydrologic modeling. Agriculture ARS-S-9. 76 pp.

Table 3. Values of Watershed Index W. (Assuming AMC = II)

Land use or cover	Farming treatment	Hydrologic Condition	Soil Group			
			A	B	C	D
Native pasture or grassland	-	Poor	70	80	85	90
		Fair	50	70	80	85
		Good	40	60	75	80
Timbered areas	-	Poor	45	65	75	85
		Fair	35	60	75	80
		Good	25	55	70	75
Improved permanent pastures	-	Good	30	60	70	80
Rotation pastures	Straight Row	Poor	65	75	85	90
		Good	60	70	80	85
	Contoured	Poor	65	75	80	85
		Good	55	70	80	85
Crop	Straight row	Poor	65	75	85	90
		Good	70	80	85	90
	Contoured	Poor	70	80	85	90
		Good	65	75	80	85
Fallow	-	-	80	85	90	95

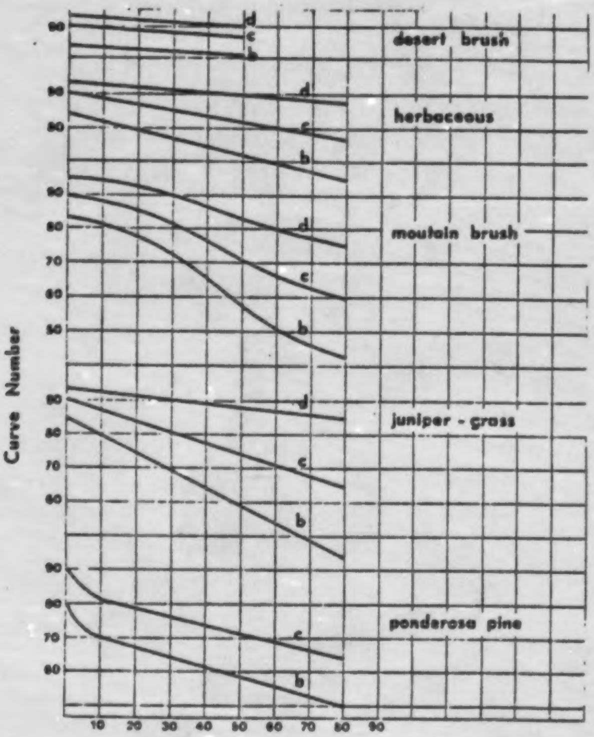
Table 4. Adjustment of Watershed Index W for Antecedent Moisture Condition

W value for AMC = II	AMC = I	AMC = III
100	100	100
95	87	99
90	80	98
85	70	97
80	65	95
75	60	90
70	50	90
65	45	85
60	40	80
55	35	75
50	30	70
45	25	65
40	20	60
35	20	55
30	15	50
25	10	45

Cover Density as Percent

Fig. 1

HYDROLOGIC SOIL - COVER COMPLEXES
AND ASSOCIATED CURVE NUMBERS



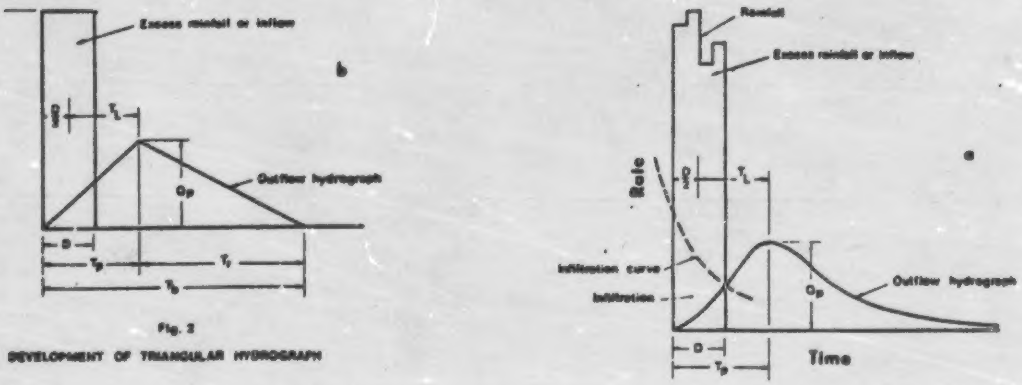

Excess rainfall or inflow
b
D/2
T_L
Q_p
Outflow hydrograph
D
T_p
T_r
T_b
Rainfall
Excess rainfall or inflow
a
Rate
D/2
T_L
Infiltration curve
Infiltration
Q_p
Outflow hydrograph
D
T_p
Time

Fig. 2

DEVELOPMENT OF TRIANGULAR HYDROGRAPH

Figure 2

Economic Analysis of Watershed Projects

by
Hans M. Gregersen

College of Forestry
University of Minnesota
March 1979

Introduction

For the hydrologist or watershed manager concerned with action programs and getting technically sound project proposals implemented, economics is of central concern — as are politics, social pressures, etc. This is the basic rationale for including an economic perspective in this course. While the academic hydrologist at times can quite justifiably ignore economics and politics in his search for the "best" technical approach to a watershed problem, the practitioner — who is of central concern to this course — cannot ignore the broader picture, i.e., the conditions which determine the commitment and capacity to implement hydrology projects.

The present paper presents a descriptive outline of some essential economic considerations, as discussed in a forthcoming guide to economic analysis of forestry projects (Gregersen and Contreras, in press). It also summarizes some "lessons learned" from a recent review of a number of studies which have attempted to apply economic analysis to watershed projects (Gregersen and Brooks, 1978).

Watershed objectives and project planning

Most land-use related projects involve implications in terms of changes in water quality and/or quantity. Thus, most such projects should include explicit consideration of water related impacts and of potential activities to achieve acceptable watershed protection standards. In some cases the major objectives of a project maybe water related and constitute the reason why the project is being considered and proposed. In other cases, water related concerns may merely enter the project analysis in the form of constraints on other project activities.

Different water-related objectives and/or constraints apply in different situations. Thus, for example, project objectives will vary widely with climatic and landform conditions as well as other factors. Appendix I presents a schematic overview of objectives which tend to dominate in different climatic regions. Regardless of objectives, constraints and other conditions, a consistent approach to project planning is needed.

The overall nature of project planning is described in several documents (FAO, 1974; Watt, 1973; references cited in both these documents). Basically, project planning involves a) definition of objectives, b) identification of alternatives to meet objectives, c) design of alternatives in terms of specific required inputs and outputs, d) analysis or appraisal of alternatives, and e) choice among alternatives. It is a dynamic and iterative process which uses feedback from past and on-going operations to improve future project planning activities.

The focus of this paper is on one of the elements in the overall planning process, namely analysis or appraisal. We limit ourselves to the economic analysis and appraisal process, recognizing full well that most projects involve other appraisals, including: a) technical appraisal (a main subject covered in the present course), b) commercial appraisal, or the consideration of the availability of inputs when needed and the actual uses or requirements for outputs, c) institutional and organizational appraisal, which deals with the consistency of a given project alternative in terms of the institutional structure existing and the organizational capacity to undertake a project; d) managerial appraisal, or the consideration of whether or not in fact there is the managerial capacity available to implement and execute a given project; and e) financial appraisal, or the consideration of budget implications and financial profitability. Some of these types of appraisals have been discussed already in this seminar. Others will be covered at a later stage. Some will not be discussed, since they are outside the scope of this seminar and its objectives.

The basic framework for an economic analysis

An economic analysis is carried out to provide information for decision-making on the costs and benefits or economic impacts associated with a project and the relationship between costs and benefits, e.g., whether the benefits exceed the costs for a given project alternative.

The emphasis here is on economic analysis from a national, public point of view, as distinct from the closely related financial analysis, which is of central concern to private entities. The public sector is also interested in financial considerations, since a project cannot be undertaken unless it is financially viable, i.e., within the budget limits of the public sector or agency considering the project. A financial or budget analysis for a watershed project is fairly straightforward and involves consideration of financial (money) outflows and inflows for a given entity or group of entities.

There are two main applications of economics in project planning. First, we are interested in the economics of alternative designs (or project opportunities) to achieve the same objective(s). This involves analysis of "mutually exclusive" project alternatives. Second, once the "best" design for meeting a given objective has been chosen, i.e., the economically "optimum" design, economics is relevant in terms of deciding whether or not in fact the project will be undertaken, when other known uses for scarce resources are considered.

Economic analyses of watershed projects are no different in principle or concept than economic analyses for any other type of project. Basically, in an economic analysis we are concerned with economic efficiency associated with alternative allocations of resources, i.e., how to achieve the greatest benefits with given resources, or how to minimize the expenditure of resources in achieving given benefits. Thus, the general concepts and guidelines presented in FAO's Economic Analysis of Forestry Projects (EAFP) are valid also for watershed related projects. However, some analytical issue and empirical problems are particularly important for such projects. Some of these issues and problems relate to economic factors, and they are the main subject of this paper. Others relate primarily to technical factors and their treatment is properly the task of hydrologists; many of these have been discussed in earlier sessions of the course. Thus, we do not discuss them further here, other than in terms of how the economist can interact with the hydrologist in determining what physical input-output information is needed in order to carry out an economic analysis. A basic point is that the physical relationships must be quantified before an economic analysis can be carried out. Thus, the present discussion proceeds under the assumption that such information can be generated. Given the fact that the lack of such information is in practice the major bottleneck encountered in most watershed project appraisals, it may seem that this assumption is made here to avoid a major problem. In fact, it is made to emphasize the point that the economist cannot solve the information and data problems associated with watershed projects. What he can do is to a) suggest a systematic approach to identifying direct and indirect negative and positive impacts associated with a project, and b) point out what information and data are needed for him to be able to value these various impacts.

Time to peak, T_p , is estimated from a consideration of both rainfall and watershed characteristics. A relationship often used is:

$$T_p = .5D + .6T_c$$

where D = duration of excess rainfall in hours (for convective storms, this can be equal to the duration of rainfall).

T_c = time of concentration in hours, which is estimated from the following equation:

$$T_c = .0078\, L^{.77}\, S^{-.385}$$

where L = length of the watershed along the main stream from the outlet to most distant ridge in km.

S = average slope of the main stream, a dimensionless ration of difference in elevation between outlet and most remote point to length of watershed L.

For most cases, the constant K has a value of 0.75 if the units are similar for both sides of the peak flow equation.

Literature

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Particular issues of concern in hydrology projects.

Based on review of a number of hydrology/watershed management projects in developing countries, it appears that there are some specific analytical and empirical issues which are particularly common for watershed projects. These are discussed in the remainder of the paper. The discussion is in most cases taken directly from an earlier study (Gregersen and Brooks, 1978).

The specific points selected for further treatment are the following:

1. Consideration of alternative means for achieving goals.
2. Determination of project scope and context.
3. Identifying costs for watershed projects.
4. Identifying benefits for watershed projects.
5. Treatment of benefits and costs in multiple purpose projects.
6. Presenting cost and benefit information in an appropriate form.

The fact that there are only six points listed does not mean that they are the only ones of concern to the analyst of a watershed related project. For a more systematic discussion of the entire range of issues encountered, the reader is referred to EAFP and FAO (1974).

In order to provide common empirical reference points during the discussion of each of these, two case study analyses of projects involving watershed considerations are summarized in Section 6. These two examples are then referred to in Section 7, which provides a discussion of the six points listed above.

Examples

The first of the examples is an economic analysis of alternative logging systems. The objective of the analysis is to find that system that maximizes net revenue subject to a constraint on maximum allowable sediment discharge. It is an example of an economic analysis to provide information for an operational decision where water related concerns are entered as a constraint.

The second example illustrates in summary form an economic analysis of a major watershed project designed to reduce the rate of sedimentation in a reservoir, thereby extending the useful life of the reservoir and producing additional downstream benefits. The project also involves several other elements, including wood production in combination with watershed protection, pasture improvement, and general improvement of upstream agriculture.

Example No. 1: Watershed Considerations as a Constraint in a Project

The growing worldwide concern for environmental protection makes this type of example relevant.

A 20 ha woodlot is to be harvested. The lot occupies land along a river with an average slope of 20–30%. In order to prevent erosion and decrease resulting sediment flows, a clearcut will not be allowed by regulatory agencies. For this reason a selective cut will be made. However, it is anticipated that with standard logging techniques about 4 tons of sediment per hectare will enter the river the first year after the harvest. This amount of sediment is considered unacceptable by authorities and they will not issue the harvesting permit unless measures are taken to reduce sediment to no more than 2 tons per hectare. Thus, the forest manager must find an alternative that will reduce sedimentation of the river by at least 2 tons/ha/yr at the lowest cost possible, i.e., he is searching for the least cost alternative for logging the area that will meet the constraint.

Harvestable volume on the woodlot is 300 cubic meters/ha which can be sold for $10/cubic meter.

If all 20 ha had been harvested using standard methods, it is estimated that the following costs and returns would have obtained:

Returns:

300 cubic meters/ha x $10/cubic meter x 20 ha equals $60,000

Costs:

labour: 1000 man hours x $2.00/hr equals $2000
tractor: 250 hours x $25/hr equals $6250
loading/transport: 120 hours x $20/hr equals $2400
total cost: $10,650

Net revenue:

$60,000 minus $10,650 equals $49,350.

However, as mentioned the standard method is not acceptable because of the high sediment discharge associated with it. Two alternatives are proposed that would meet the maximum discharge restriction.

The first feasible alternative consists of leaving a 25 m wide buffer strip (no cutting) along the river. The woodlot has a shoreline of 1600 m, therefore, cutting would be reduced to a total of 16 ha instead of 20 ha. This means a loss of 4 ha of timber or 300 cubic meters x 4 ha x $10/cubic meter which equals $12,000 of revenue foregone. This is considered a cost for this alternative. It is assumed that other costs would be reduced by 20 percent since only 16 ha could be harvested. Thus, costs other than revenue foregone would decrease to $8520 (20 percent less than $10,650). Total cost of this alternative would be $20,520 ($8520 plus $12,000).

The second alternative which meets the sediment discharge requirements consists of establishment of 40 m filter strip in which no machines are allowed. All commercial timber (i.e., 300 cubic meters/ha) on this 6.4 ha filter strip can be cut but must be winched out at a higher cost. On the 6.4 ha of the filter strip costs are estimated to be $8,094. For the remaining 13.6 ha costs will drop to an estimated $7,242 to reflect reduction in area logged. Thus, total cost of this alternative will be $15,336.

Assuming that these are the only two alternatives considered that meet the sediment discharge restriction, we would choose the lowest cost alternative or the filter strip approach. Revenue would be $60,000 as before and cost would be $15,336, for a net return of $44,664, which compares with a net return of $29,480 in the buffer strip alternative. The information generated in this analysis further indicates that the cost of the sediment discharge restriction would be $49,350 minus $44,664 or $4,686.

Example No. 2: Economic Analysis of a Watershed Protection and Management Project*1

Background on Project

Project title:
Watershed protection for the Sierra Reservoir.

Project situation:
Some years ago, a reservoir was built along the Sierra River to provide storage of water for downstream use during periods of low flow. Downstream uses include irrigation on some 9500 ha and domestic water use by the local population. It has been found after five years of operation that the reservoir is silting in at a much faster rate than initially anticipated, thus reducing

effective capacity and ability to meet water requirements downstream. Siltation is occurring at a rate of 4 million cubic meters per year. Present reservoir capacity is down to 100 million cubic meters. At the present rate of siltation, it will only be four years before capacity is reduced to a point where it can no longer meet estimated water requirements of downstream users. (Domestic water use is increasing at a rate of about 6.19 percent per year, while irrigation use is fairly constant.)

Project goal:

To prevent the reduction (or loss) of water related downstream benefits (those that would be lost without the project include crop values and health and satisfaction associated with domestic water use), the project would extend the effective capacity and life of the reservoir by reducing the rate of siltation from 4 million cubic meters/year to 1 million cubic meters/year. Since there was apparently no problem of flood damage with or without the project, flood prevention was not included as a goal. It could be added in as a goal and treated in exactly the same way, if it was a problem.

Project points of view:

(a) Downstream users of water have a direct interest in maintaining the capacity of the reservoir so that they can continue to receive water during the dry periods when river flow is inadequate to meet requirements;

(b) Upstream users of the land which would be affected by the various conservation measures proposed for the project are interested in how such measures would affect them. If effects are negative, some form of compensation may be included in the project plan;

(c) The nation at large is concerned with increased crop consumption, improved welfare of domestic water users, and losses or gains incurred by upstream land users.

The point of view adopted in the analysis is primarily that of the nation, although the other two viewpoints are also considered.

Identification and Valuation of Project Costs

To accomplish the project goal, the following project components have been proposed in the technical design and analysis:

(1) Establish protection forest on the most critical areas where no other activity should take place because of slope or critical nature of soil protection.

(2) Establish protection/production forests on areas that need permanent protection but which are less critical so that some forest utilization can take place on a controlled basis.

(3) Build terraces on some of the most critical areas with very unstable soils.

(4) Manage and maintain pasture lands on a rotation, based on their carrying capacity and ability to regenerate. This will primarily involve control and policing activities together with technical assistance.

(5) Establish forest management on existing natural forest areas. This would include control on harvest and other activities, watershed protection inputs into access road establishment, inventory and other information gathering activities.

(6) Establish an overall watershed management and administration unit within the regional government to supervise and control implementation of an integrated watershed management programme for the whole watershed, including the above elements. Include extension services for local farmers.

In the project documentation, appropriate technology, input requirements and timing for each of the project components were analyzed. Based on an initial survey of the total watershed of 17,500 ha, the scale of each of the project components was determined, as shown in Table 1. Average input requirements per ha were estimated and applied to the total areas to arrive at total labour, equipment, and other input requirements. These input requirements together with unit value estimates were then used by the economist in valuing the project costs, which are summarized on lines 4 through 8 of Table 4.

In developing economic values for inputs, only unskilled labour was shadow priced. Other inputs were valued in the economic analysis at their financial or market price values.

A project period of 26 years was considered appropriate, considering the relevant social discount rate of 12 percent. For discussion of choice of project period and discount rate, see EAFP.

Identification of benefits

Reservoir demand (i.e., the demand on water from the reservoir which would not be available without it)*2 is estimated at 86 million cubic meters in the first year (year 0) of the project as shown on the first line of columns 5 or 6 of Table 2. The capacity of the reservoir is 100 million cubic meters at present (start of project) and is decreasing by about 4 million cubic meters per year due to siltation. (See Col. 2 of Table 2). Thus, in about four years from the present the estimated capacity of the reservoir without the project would just be equal to demand. From then on, the reservoir would not meet the requirements for water from it.

With the project, it is estimated that the rate of siltation can be reduced to about 1 million cubic meters per year. Thus, the reservoir will be able to meet requirements for a longer period of time, although eventually, even with the project, demand for water will outstrip the capacity of the reservoir. (This will occur in year 10. Compare Cols. 3 and 6.)

A first reaction might be to use the difference between the without and with project capacities as shown in Col. 4 as a measure of benefits. However, this would overstate benefits, since even without the project, the reservoir could satisfy demand for four more years. With or without the project, the benefits would be the same during those first four years and, thus, the benefits due to the project would be zero during that period (years 0–3). For the next six years (years 4–9) capacity with the project would still be above demand. Thus, with the project, the benefits due to the project for this period would be the difference between estimated demand and supply without the project, or the demand deficit which would start to be felt in year 4 if the project were not undertaken. (This is the difference between raw items in Cols. 5 and 6). In year 10 demand would start to outstrip supply even with the project. Thus, from year 10 and on to the end of the project, the appropriate benefit figures would be the differences in capacity with and without the project (i.e., the difference between cols. 2 and 3). Using the above approach, the increased water use due to the project is identified and shown for each year in Col. 7 of Table 3.2.

The figures shown in Cols. 5 and 6 are gross figures which include evaporation from the reservoir, estimated to average about 54 million cubic meters per year. Since the evaporation would be approximately the same with and without the project, there is no need to adjust the figures shown in Col. 7. They represent net increases in effective water use.

In addition to the direct benefits associated with increased reservoir capacity, there will be some timber related benefits from the combined production/protection plantings. Based on experience elsewhere, these are expected to be as shown in Table 3. In years 6 through 10 there will be some minor thinning volumes available and in years 17 through 21 there will be final harvest volumes available.

In addition to the water and timber related benefits, the following indirect benefits were identified but not quantified in the study:

(a) Eventual increases in livestock production due to regulation of grazing on watershed lands. (At present, many of the pastures are marginal due to overgrazing). The project would restore these lands.

(b) Aesthetic values will increase as the land is rehabilitated.

(c) Access roads required for protection and other watershed management activities will permit faster and cheaper access by farmers to markets and increased mobility for extension personnel so they can reach more farmers.

(d) The project is expected to result in an increase in water quality in addition to quantity. A reduction in suspended loads carried over the reservoir dam will decrease the need for maintenance on individual irrigation installations.

Valuation of benefits

Based on studies of crop increases made possible by irrigation, it was estimated that irrigation water flowing out of the reservoir would return a net of P2 per cubic meter of water.*3 Since (1) the major portion of the water is used for irrigation, (2) there was no feasible way of placing a value on the water used for domestic purposes, and (3) there is no feasible way of allocating the increased water made possible by the project to irrigation and domestic use, it was decided to value the domestic water at the rate used for irrigation, namely P2 per cubic meter. This was recognized to be a conservative estimate. Using this value per cubic meter and the water increase figures in Col. 7 of Table 2, the corresponding annual water related benefits from the project were determined as shown in row 1 of Table 4.

The wood production benefits were valued at P290 per cubic meter on the stump. This value was a parity price based on the value of imported wood. The parity price was adjusted down by 10 percent to reflect the lower quality of project wood. Total wood production benefits are shown on line 2 of Table 4.

Other benefits were not valued due to inadequate data or to the inappropriateness of attempting to quantify values, e.g., for the aesthetic benefits.

Comparing costs and benefits

As indicated on line 9 of Table 4, there is a net cost involved in the project for the first four years, after which the value flow turns positive and increases steadily over the life of the project. Using a rate of discount of 12 percent, we arrive at a Net Present Worth (NPW) for the project of some P292 million.*4 The rate of return (ERR) of the project would be well in excess of 50 percent.

The high returns to this project can be explained quite easily. Since the reservoir was already in place and its cost represented "sunk costs," they were not included in the analysis of the project. Thus, the small amount of additional expenditure required for the watershed protection activities (the project) were compared with the returns which actually include the total incremental benefits from the reservoir. Obviously, if one were analyzing a new reservoir project, the situation woudld be quite different, since the substantial expenditure for the reservoir would have to be added into the cost stream for the project, while the benefits would remain approximately the same.

Discussion of Issues

The two examples presented are representative of the types of economic analyses one encounters for watershed related projects. The following discussion outlines some of the major issues which arise concerning these examples and points to watch when applying the guidelines presented in EAFP to watershed related projects.

Considering alternative means for achieving project goals

One of the basic points made in EAFP is that project planners should explore alternative means for achieving given project goals. If only one alternative is presented to the decision-maker, his only decision is whether to accept or reject it. On the other hand, if information is presented which permits him to look at a range of alternative means for achieving a goal, then he can more thoroughly consider and weigh the implications of different courses of action.

In Example 1 two alternatives to the standard logging approach were considered explicitly in the analysis. If other known alternatives had been available then they should also have been considered. In this case, the objective was to find the lowest cost alternative that met the maximum allowable sediment discharge restriction or constraint. Thus, one should note that costs and benefits for the standard logging approach were used only as a basis for comparison since it was, by definition, an unacceptable alternative due to the fact that it did not meet the constraint. Thus, actually only two alternatives were compared, the buffer strip one and the filter strip one. If others had been available (technically defined) they could very easily be included in the analysis.

The appraisal did not consider alternatives in the case of Example 2. However, there appear to be two which might have been considered. The first is the use of dredging at some future date to maintain reservoir capacity equal to demand. The second is the expansion of the reservoir to increase capacity so it can meet demand even when siltation occurs. In addition, the report on which this example is based did not discuss alternative technologies and scales for project components, nor did it go into the relative advantages of alternative timings of project activities to more efficiently achieve the goal of the project. Finally, although some of the project components were separable in terms of costs, the analysts did not have information on which to base a seaparation in terms of benefits. Thus components were not analyzed separately and it was not possible to evaluate alternative combinations of project activities to find a more efficient overall solution for meeting the goals.

Determining project scope and context

A major question facing project planners is what to include and what not to include within the scope of a given project.

From a practical point of view, it boils down to a question of where to cut off the endless chain of effects or impacts associated with a given project. The theoretical answer is: "Include all the impacts." The practical answer is: "Include all those impacts which you can identify and which appear to be lage enough relative to the direct and immediate impacts to make a difference in the cost and benefit flows." The object of a project evaluation is to generate the information needed to make a sound decision as to whether or not the project has benefits exceeding costs and, if so, whether the benefits exceed the costs by a large enough margin to make it worthwhile to commit scarce resources to the project rather than to some alternative use. If the direct benefits associated with a project are large enough relative to costs to make the project worth undertaking from an economic point of view, then spending a large amount of effort and funds on further analysis of all the various indirect impacts will not be worthwhile. However, if the project is marginally unacceptable, then there is a much stronger case for detailed analysis of indirect impacts. No general guidelines can be put forth here on how to determine the appropiate cutoff for considering indirect impacts. That will depend on each project situation, the knowledge of the project planners and staff specialists, the cost and time involved in generating information on indirect impacts, and the objectives of the institution sponsoring the analysis.

In the case of Example 1, the scope was very narrow, mainly due to the fact that the project involved a very small area and probably had insignificant indirect impacts. The example illustrates well the type of brief, uncomplicated analysis associated with operational decisions. Once this particular situation had been analyzed and the best logging method chosen (the lowest cost method that met the constraint) it is likely that that method was accepted and used for other similar logging situations without further analysis, i.e., this simple analysis served as the basis for developing an operational guideline for logging that says: "In situations of riverside logging, a filter strip system is the cheapest alternative logging system which meets the specified maximum allowable sediment discharge constraint."

In the case of Example 2, the project scope included the major impact elements, with the exception that there was no consideration given to how the project would affect the farmers upstream on the watershed lands who would have to change their operations due to conversion of land to forest, or due to curtailment of grazing on critical watershed lands. Similarly, there was no quantitative analysis of the positive impacts on farm economies associated with the improved road network and the increased mobility and availability of extension services. Ideally, these should have been included in the analysis, and one would expect — even without having information on the project background and area — that it would have been possible to provide some more explicit treatment of these impacts.

The question of project scope is closely related to other aspects of project definition: (1) project points of view, and (2) cost and benefit identification.

Concerning project points of view, Example 1 can be identified with two: the logging operator (or company involved with logging the area), and the public point of view concerning sediment discharge. In this case, the public point of view has been expressed in terms of the maximum allowable discharge regulation and thus does not need to receive further consideration in the analysis.*5 The logging operator or company point of view (assuming that this is a private entity involved) is really the point of view from which the analysis is carried out, i.e., the question is: "What is the minimum cost we have to incur to achieve the constraint?" If the public sector is doing the logging, the question remains the same from an economic efficiency point of view.

Example 2 is somewhat more complex in terms of points of view. As stated in the text, there are three points of view identified, namely the downstream water users, the upstream land users and the national point of view which incorporates the other two points of view within an overall objective function.*6 The downstream users' point of view defines the scope of the project at that end: the project should be defined broadly enough to include the necessary downstream costs to achieve the benefits accruing to the downstream users. On the other hand, the upstream land users' point of view defines the scope of the project at that end: the project should be defined broadly enough to include those costs and benefits for that group that occur because of the project. As mentioned earlier, there did not appear to be adequate consideration given to this point of view and the associated costs and benefits.

Consideration of points of view helps the analyst in identifying the appropriate scope and in identifying relevant costs and benefits for use in the economic, financial and social analysis for the project. The following two sections discuss cost and benefit identification in terms of economic efficiency analysis.

Identifying costs

One can specify three main categories of costs involved in watershed projects. These are.

Structures and work costs: These include costs of dams, gully plugs, construction of contour furrows or terraces, channel construction or improvement, road relocation, retainer walls, etc., and maintenance of these structures and facilities.

Vegetation manipulation costs: These mainly include costs of removal of vegetation and planting and management costs associated with the establishment of new vegetation.

Value of outputs foregone: Even eroded or deteriorated lands may be producing values through grazing, subsistence farming, etc. These activities may have to be curtailed for a period of time in order to restore land to some higher level of productivity. The value of such production foregone should be included as a project cost. In the case of a protection project, timber harvested per unit area may be reduced due to the introduction of buffer strips along rivers, streams, roads, etc. Selective harvest may have to be imposed on steep hillsides which may in turn reduce the present value of harvests. This reduction is a cost.

The first two categories of costs are quite obvious, and both examples in Section 6 treated these in an adequate fashion. The third category — value of outputs foregone -- is also relevant to both cases. In Example 1, it can be noted that the analyst treated the value of timber foregone through creation of a buffer strip as a cost. He could also have merely reduced the total benefit figure by this amount, thus treating this value foregone in terms of benefits. Either way would have produced the same result, since the objective was to arrive at the alternative with the highest net return.

In the second example, there were values of outputs foregone from changes in land use that should have been considered but were not, as explained in the previous section. This supports the point made earlier that project scope points of view and cost and benefit identification are closely interrelated. Since the upstream land users' point of view was not adequately defined the analyst also missed identifying explicitly changes in value of output associated with upstream land use due to restriction of grazing on some lands and shift in land use from agriculture to forestry on other lands.

Identifying benefits using the "with and without" test

The basic approach suggested for identifying costs and benefits involves use of the "with and without" test. Basically, this means that the analyst asks and answers the question: "What would the situation likely be without the project over the period of years contemplated for the project and what would the situation likely be with the project?"

The particular point to emphasize here is that the "without" project situation is not the same as the present situation for most types of watershed projects. Thus, over time, without the proposed watershed project, soil conditions might deteriorate, erosion might increase, etc. The analyst has to make sure that these changes are taken into account. Figure 1 illustrates a typical situation. As noted, at time 0, production is at level X. Without the project, conditions would deteriorate until in year n production would have decreased to Y. With the project, it is estimated that production will increase to Z. The point to note here is that both Z minus X and X minus Y are legitimate benefits to be attributed to the project. Thus, the analyst will not only need to estimate the increase in production which will be possible (i.e., Z-X) but he will also have to make an estimate of the losses which will be avoided (i.e., X-Y). Example 2 illustrates this point.

Application of the "with and without" test also brings out another point related to benefit identification and valuation (which is also illustrated by Example 2). The point is that merely because a project changes some physical dimension in a positive way, this does not necessarily mean that there is a benefit involved. In Example 2, the project starts immediately to reduce the level of siltation in the Sierra reservoir and thereby increases the effective capacity of the reservoir. However, even without the project the level of capacity of the reservoir is in excess of demand and will continue to be so for the next 4 years. Applying the "with and without" test, the analyst can see that consumption of water (the relevant benefit parameter) will remain the same with or without the project for this period. Thus, the benefit (losses avoided) due to the project will be zero during the first four years, or until the capacity of the reservoir without the project would have fallen below requirements for water. This point applies more broadly to many different types of watershed projects.

The above point relates to the fact that in an economic efficiency analysis, benefits should be measured in terms of human consumption. Thus, for example, the hydrologist may provide an estimate of tons or cubic feet of soil loss that can be avoided by undertaking a given project. But this information is not enough for an economic analysis. In order to value the benefits from the project, such losses avoided have to be translated into a schedule of crop or other consumption losses avoided. Thus, agricultural experts have to come up with a relationship between soil loss and crop production or soil loss and production of some other consumption item. This consumption loss can then be valued and used as the benefit in the economic efficiency analysis.

Treatment of Benefits and Costs in Multiple Purpose Projects

A point worth mentioning here is the need to use care and caution in identifying costs and benefits associated with multiple purpose projects which include a watershed management element. For example, in some cases, trees planted on denuded lands as part of a watershed protection or restoration project will also be managed for controlled harvest for fuel or other products. In such cases, both types of benefits will have to be included in the analysis. Of course, any associated costs involved in harvest will have to be subtracted, if roadside value for the harvest is used instead of stumpage value. Proper allocation of tree planting costs to the watershed benefits and the wood output benefits is difficult. If timber production is the main objective of the project with watershed protection or restoration as a secondary purpose, then one practical approach would be to allocate the basic costs to the timber objective. Any additional costs of vegetation management to achieve the constraint or watershed objective would be allocated to the watershed component of the project. Similarly, in the case of logging road redesign to meet certain watershed constraints or objectives, the equivalent of the minimum road cost to get the timber out would be attributed to the timber element, while the additional costs associated with higher standards to meet the watershed objectives would be allocated to the watershed element.

In the case of a primary purpose watershed project, the cost of tree planting or other activities would be associated with the primary purpose and benefits, while timber benefits would be treated as secondary benefits. As mentioned earlier, it is important in such cases to remember to subtract any secondary costs associated with the timber production up to the point of valuation of the timber (e.g., stumpage level, delivered log level, etc.).

Timing of Costs and Benefits — Presenting cost and benefit information

Most watershed projects tend to be longer term projects in the sense that the inputs occur over a considerable period of time and the benefits accrue over an even longer period of time. Further, benefits and costs are constantly changing over time.

A main problem is to develop a sound estimate of the timing of the benefits. Restoration projects generally take time to implement. Full productivity is restored slowly in most cases. For example, if trees are planted on a deteriorated watershed, the full protective effect on erosion control will take some time to achieve.

In order to keep track of the project assumptions regarding the build-up to project benefits and costs over time, it is essential to use appropriate physical flow tables and, ultimately, properly designed value flow tables. (Such tables are shown as Tables 3 and 4 in Example 2 in this paper.)

Treatment of uncertainty

Watershed related project are particularly subject to great uncertainty in terms of the values of costs and benefits used. Thus, it is important that project appraisals include explicit treatment of uncertainty. Neither of the two examples presented earlier did so, and that is perhaps a typical situation found in most economic appraisals.

There are some simple techniques, such as sensitivity analysis and break-even analysis, which can be applied rather easily and cheaply in most cases. Basically, sensitivity analysis involves varying assumptions concerning the values of key parameters and then testing the sensitivity of the chosen measures of project worth to such changes. A break-even analysis is aimed at identifying values of key parameters which would switch the profitability of a project from acceptable to unacceptable levels (see EAFP, chapter 10).

Summary and Conclusions

The present paper presents an overview of some special problems associated with economic analyses of watershed projects. No attempt is made to provide systematic, detailed guidelines for project analysis, since these are covered in FAO's Economic Analysis of Forestry Projects (EAFP). The paper presents some examples and case studies of economic analyses of watershed projects and provides insights into how the analyst can consider watershed elements when they are imposed as constraints on projects that have other goals (e.g., wood production).

A question remains: What lessons and conclusions can be drawn in terms of how the economist can work more effectively with hydrologists, foresters, agronomists and other technical specialists in attempting to provide improved analyses of watershed projects? Based on the discussion in this paper and a review of a number of watershed project appraisals, the following points are relevant in answering this question:

> (1) In general, it would appear that the weakest link — or the major problem — in carrying out an appraisal of a watershed project relates to the identification and quantification of the physical input-output relationships and the costs and benefits involved. Once costs and benefits have been appropriately identified and quantified in physical terms, there do not appear to be any special problems involved in valuing them and comparing them in terms of the measures of project worth commonly used. With regard to this point, it would appear that there are a lot more data available on input-output relationships than is generally thought and used in projects. The problem is that very little has been done to bring this information together in a practical form that can be used by the general project planner. Thus there is a need to spend a lot more time and effort in developing comparative studies and translating highly technical information into practical guidelines that can be used by project planners.
>
> We fully recognize that the technical specialist and researcher may argue that each case is a different one and that it is impossible to transfer the experience from one situation to another situation. While we agree that there is seldom a situation where experience from one

project fits perfectly the conditions for another project, we also suggest that most analysts are dealing with averages and orders of magnitude in their attempts to analyze new projects, particularly in developing countries. They have no choice.

(2) Economists and the other technical specialists have to interact at all stages in the project planning process, for the economist cannot carry out an economic analysis unless he has the basic physical input-output information on which to base his analysis. The economist has to make known at an early stage his information needs. If he does not, then he can rightly be criticized. However, the primary responsibility for generating the needed information lies squarely on the shoulders of the hydrologist and other technical specialists. This is not within the economist's area of competence. His main responsibility starts when the appropriate information has been generated. We stress the word "appropriate" since in a number of cases it has been observed that a greal deal of information has been accumulated for a project, but it is not the right information for the purposes of quantifying and valuing costs and benefits. Thus, for example, it is not enough to have information on average per ha soil losses under various conditions. The agronomist and soil experts must make a specific link between soil loss and crop loss, for benefits in this case have to be specified in terms of consumption losses avoided. We do not "consume" soil, we consume the products grown on it. In order to value such product losses avoided through implementation of a watershed project, we will need to link soil loss to crop production changes. The same argument holds for other types of relationships.

With the above in mind, we strongly recommend that if an economic analysis is to be carried out for a watershed project then the economist should be included in the planning process at an early stage so he can make his information needs known. It may well be that the information he needs cannot readily be generated with available time and funds. In such cases, it will not be possible to carry out an economic analysis that considers both costs and benefits. Rather, the economist will have to stick to a cost-effectiveness analysis or some other types of partial analysis. Or, at the extreme, he will have to state that an economic analysis is not possible, given the present state of knowledge and data availability. However, at this point we should stress again that, in many cases, more information is available than is generally thought and used. It would be well worthwhile to spend some time and effort on bringing together such information in a form that is readily understood by general project planners and decision-makers.

Notes

*1 Adapted from a project in the Andean foothills of a South American country.

*2 I.e., release of water in dry season to meet requirements during that period. It does not include the water used that would have been available without the reservoir, i.e., the requirements which would have been met from normal precipitation and river flow without it.

*3 I.e., after subtracting from final crop value all costs back to the reservoir, e.g., farming costs, marketing, water distribution, etc., but excluding any sunk costs.

*4 The rate of discount was given to the project planners by the national planning office and represents the rate used for evaluating all public projects in the country.

*5 Unless, of course, the analyst is also asked to look explicitly at the costs and benefits associated with different levels of sedimentation. This, however, is a separate question.

*6 As mentioned in EAFP this objective function relates to project impact on aggregate consumption.

Appendix 1

Watershed Management Objectives Relevant for Different Climatic Regions

The following table (Gregersen and Brooks, 1978) presents a general view of the variety of watershed management objectives which may be relevant for different climatic regions. Obviously, there are exceptions to such a generalized ranking. But it does indicate some general considerations. Specific site characteristics and other factors such as proximity to population centers and level of economic development may in some situations reorder the watershed management priorities listed. For example in a mid-latitude mixed forest with abundant rainfall and water supplies, the management of municipal watersheds for maintaining or perhaps increasing the quantity of water yield to satisfy the demands of an increasing population may be a major objective. Conversely, the goal of increasing the quantity of water in many desert ecosystems may be unrealistic from a watershed management viewpoint because of the lack of opportunities to do so.

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TABLE 1

Areas associated with each project component

Component	Hectares
Protection plantings	760
Protection/production plantings	870
Terraces	320
Pasture use control	3 850
Natural forest management	3 160
Watershed planning & Adm.	(17 500)[1]

[1] Including the parts of the watershed not requiring direct action.

Table 4.- SUGGESTED IMPORTANCE OF WATERSHED - WATER RESOURCE MANAGEMENT OBJECTIVES FOR DIFFERENT CLIMATE - VEGETATION REGIME OF THE WORLD.

			OBJECTIVES [2]					
Climate[1]	Precipitation Annual Amounts (cm)	Comments	Increase Quantity	Reduce Flooding	Drainage of Wetlands	Minimize Erosion & Sedimentation	Improve Water Quality	Minimize Wind Erosion
Boreal Forest	25 to 75	6 months below freezing	3	2	1	3	2	4
Mid-Latitude Mixed Forest	750	hot summers cold winters	2	2	3	1	2	4
Mid-Latitude Coastal Evergreen Forest	40 to 7250	mild, humid high winter precip.	3	2	4	1	2	4
Mediterranean Scrub Woodland	40 to 90	warm, dry summers wet winters	2	2	4	2	3	3
Mid-Latitude Steppe	30 to 75	wet, hot summers cold winters	3	2	4	1	2	2
Desert	<25	evapotranspiration exceeds precip.	1	2	4	2	3	2
Tropical Rain and Semi-deciduous Forests	165 to>760	rainfall evenly distributed, warm, wet	4	2	3	1	3	4
Tropical Savanna and Thorn Scrub Woodland	75 to 130	pronounced wet and dry periods	2	2	4	1	2	3
Mountain								
- Precipitation limiting in adjacent areas	variable	generally an increase in precip. with elevation	2	2	4	2	2	4
- Precipitation abundant	variable		3	2	4	1	2	4

[1] As classified by Rumney (1968); Polar ice cap and tundra climates were not considered in this analysis.

[2] Objectives: 1-Primary; 2-Secondary; 3-Usually not of major importance; 4-Little or no importance. It should be noted that such objectives are highly dependent upon individual watershed characteristics including topography, slopes, and soils, and other factors such as land use, population, and level of economic development.

Table 2 - Watershed Project: Identification of Water Benefits

(millions of m3/yr)

(1) Year	(2) Reservoir Capacity without project	(3) with project	(4) Difference with & without project	(5) Reservoir Use without project 1/	(6) with project 2/	(7) Difference in use with & without 3/
0	100	100	0	86.0	86.0	0
1	96	99	3	86.4	86.4	0
2	92	98	6	86.8	86.8	0
3	88	97	9	87.2	87.2	0
4	84	96	12	84	87.7	3.7
5	80	95	15	80	88.2	8.2
6	76	94	18	76	88.7	12.7
7	72	93	21	72	89.2	17.2
8	68	92	24	68	89.8	22.3
9	64	91	27	64	90.4	26.4
10	60	90	30	60	90	30.0
11	56	89	33	56	89	33
12	52	88	36	52	88	36
13	48	87	39	48	87	39
14	44	86	42	44	86	42
15	40	85	45	40	85	45
16	36	84	48	36	84	48
17	32	83	51	32	83	51
18	28	82	54	28	82	54
19	24	81	57	24	81	57
20	20	80	60	20	80	60
21	16	79	63	16	79	63
22	12	78	66	12	78	66
23	8	77	69	8	77	69
24	4	76	72	4	76	72
25	0	75	75	0	75	75

1/ Constrained by demand for water during first 4 years then constrained by capacity as demand outstrips supply

2/ Constrained by demand for first 10 years then constrained by capacity as demand outstrips capacity even with the project

3/ This is the measure due to the project, i.e. the difference in use with and without the project

Table 3 Inputs and Outputs - Production Forest Component

	0	1	2	3	4	5	6	7	8	9	10	11-16	17	18	19	20	21
Ha planted	174	174	174	174	174								174	174	174	174	174
Thinning harvest																	
ha							174	174	174	174	174						
m^3/ha							20	20	20	20	20						
Total m^3							3480	3480	3480	3480	3480						
Final Harvest																	
ha													174	174	174	174	174
m^3/ha													525	525	525	525	525
Total m^3(1000)													91.3	91.3	91.3	91.3	91.3

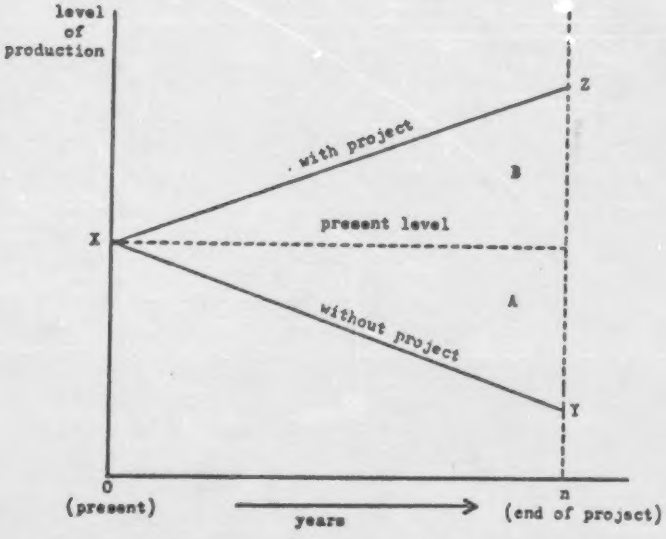
Table 4 Value Flow Table

(millions of pesos)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
BENEFITS																										
1 Irrigation & domestic use	0	0	0	0	7.4	16.4	25.4	34.4	45.6	52.8	60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
2 Wood production							1.0	1.0	1.0	1.0	1.0							26	26	26	26	26				
3 Total	0	0	0	0	7.4	16.4	26.4	35.4	46.6	53.8	61	66	72	78	84	90	96	128	134	140	146	152	132	138	144	150
COSTS																										
4 Planting protection forest	3.4	4.5	1.1																							
5 Planting production forest	1.3	1.6	1.6	1.6	1.6	0.3												1.3	1.6	1.6	1.6	1.6	0.3			
6 Terrace construction	0.8																									
7 Management costs 1/	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
8 Total	6.5	7.1	3.7	2.6	2.6	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.3	2.6	2.6	2.6	2.6	1.3	1.0	1.0	1.0
9 NET BENEFIT (COST)	(6.5	7.1	3.7	2.6)	4.8	15.1	25.4	34.4	45.6	52.8	60	65	71	77	83	89	95	125.4	131.4	137.4	143.4	149.4	130.7	137	143	149
10 Present Value at 12%	(6.5	6.3	2.9	1.8)	3.0	12.9	12.9	15.6	18.4	19.0	19.3	18.7	18.2	17.6	17	16.3	15.5	18.3	17.1	15.9	14.9	13.8	10.8	10.1	9.4	8.8
11 NPV at 12%	NPV at 12% P292 million																									

1/ including protection and extension services, maintenance and administration

Figure 1



A - losses avoided

B - production increases over present level

A Simplified Approach to Agricultural Systems

by

Milo L. Cox

Deputy Director, Office of Agriculture, Technical Assistance Bureau, Agency for International Development.

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Issues

Agriculture directly controls the economic and social life of about 70% of the world's people. The present state of this agriculture, although improving slowly, still inhibits economic progress, frustrates the improvement of rural life and encourages urban migration. Accelerated levels of economic development, political stability and human well-being depend strongly upon the rate at which the LDCs adopt measures for solving four primary agricultural issues, namely:

A. Materially enhance political response to the rural sector.
B. Significantly increase the production, distribution and utilization of food and fiber.
C. Greatly improve effective rural income levels.
D. Substantially increase the wise utilization of agricultural resources.

Performance to Date

Sporadic progress has been attained in each of the above basic issues facing the LDCs, but this progress has been slow and erratic. Rural per capita incomes have remained below one-third of urban incomes and generally have failed to increase proportionately with rises in the GNP. Farm production in absolute terms has grown, but per capita food production has remained relatively static on a world basis. Government response to the needs of the rural sector, in terms of price incentives, infrastructure, agricultural research, credit availability, marketing functions, and Ministry of Agriculture budgets has been inadequate and vast areas of potentially productive lands still remain idle.

These consraints, among others, have resulted in production levels that have about maintained the status quo These levels are too low to satisfy the nutritional needs of growing populations, too low to allow the agricultural sector to contribute substantially to overall economic growth, and too low to offer hope for an improved future to the millions of subsistence farmers saddled with present inequities.

Progress towards the attainment of acceptable rural living levels for the mass of the world's farm population is grossly unsatisfactory. Failure to substantially improve these levels of living tends to increase migration to the cities, creating new influxes of the discontented upon already smoldering urban frustration and preventing the settlement of new lands and the acceptance of modern techniques of agriculture production on the farm.

Early U.S. efforts in attempting to improve agriculture in the LDCs were directed primarily towards the transfer of the techniques of production. These techniques resulted in increased yields but markets were unreliable, inputs often expensive, credit limited and farm prices low, thus expected profits did not generally accrue. Recent improved analyses of the total economic and social environment offer much broader understanding, more viable approaches and new mechanisms by which an economic environment can be established in which agricultural progress is possible and the technology truly useful.

Constraints and Opportunities

The physical character of the agriculture of any country is largely shaped by the character of the land forms, soils and climate of the region, but what happens within the constraints imposed by physical charcteristics is closely related to economic, social and political as well as agronomic forces and the relative balance between these forces. It is the first premise of technical assistance that these forces as well as some of the physical features are alterable, that by deliberate but careful adjusment, both the direction and pace of agricultural development can be altered, and that the economic, social and political costs of such alterations need not be excessive.

Changeable though these factors are, there remain the constraints imposed by the very nature of the typical agricultural system -- which is large, ponderous, geared to biological and seasonal climatic forces, made up of thousands of widely dispersed units and controlled by the most conservative and least literate segment of the population. Because of the nature of these systems, little that is positive can be accomplished by force, quotas, penalties or other such uses of government authority. Even under the most carefully controlled conditions of a police state, these measures have resulted in disappointing output, and sometimes in agricultural chaos and governmental frustration. The second premise of technical assistance in agriculture then, is that the system must be led or pulled, not forced nor driven. There exists a diversity of tools that can be used for leading or pulling the agricultural sector towards desirable change, some of which can be used or influenced by technical assistance. Others require political action enlightened by adequate knowledge of how the agricultural system works.

Farmers' Decisions

The farmer's choices, among alternative production activities, are influenced not only by customs and habits carried over from the past, but by the incentives and opportunities to improve his income and social situation and by the risks associated with these opportunities, as he sees them. As stated in the first premise above, many of these factors are alterable. Thus, technical assistance in seeking to foster constructive change, should concern itself with the environment of incentives and opportunities for productive activity and the concommitant risks that face the individual farmer. Improvements in incentives and reductions in risks exert the pull on which the second premise is based.

The adjustable components of this environment are primarily the set of government policies affecting agriculture and the set of institutions providing services to agriculture. For example, a price policy change can provide the farmer with an incentive to produce, but he may not be able to respond to this incentive without access to adequate credit, technical, marketing, risk bearing or other services that he needs.

In any case, what happens in agriculture in nearly any country, is the sum or total of the effects of hundreds of thousands of individual farmers' decisions. The farmer hopes that the decisions he makes will be to his greatest economic and/or social advantage. His government and A.I.D. hope that the decisions he makes will be to the advantage of the country's economic and social development. Our role is to foster the selection of choices in such a way that when the farmer makes the decision that is best for him, it is also likely to be best for the development of the country in which he lives. This is the essence of helping the agriculture sector to adequately feed a growing population, contribute significantly to overall economic development and hopefully result in a better life for the people of the LDCs.

Agriculture Sector Analysis

An agriculture sector analysis is essentially a detailed study of agricultural production, distribution and utilization systems, the major components of such systems and the many factors influencing these systems. A thorough understanding of the components of an agricultural sector is necessary for the setting of realistic goals, the formulation of acceptable strategy, the development of workable plans and the structuring of implementing activities. A sector analysis, systematically applied to reasonable accurate data, should describe the main components of the agricultural sector, the relative health of the components, how these pieces fit together, how they interface with and influence each other and the sensitivity of agricultural systems to intentional or naturally occurring changes in components or factors. Also, the analysis should indicate the degree, timing and location of changes required to achieve selected goals.

Strategy formulation and planning, if they are to be truly meaningful, ought to be based on rather comprehensive in depth analysis of the sector one hopes to influence. Detailed analysis of the agricultural sector and the relationship of this sector with all other sectors in the economy are universal needs in developing countries. Interaction among and interfaces between the various components of the agricultural sector need to be evaluated by interdisciplinary groups that can bring to bear broader understanding than that provided by specialists in the many components involved in the flow of events from original inputs, through production to eventual marketing and utilization. Although such sector analyses must be closely oriented to the specific country involved, there is a universal need for this type of approach in all developing countries. Historically, where assistance groups have failed to effectively promote continuous improvement in agriculture over time, there has often been a failure to do enough analytical work to be able to predict the probable rate of development or response and to plan and decide what to do when certain progress levels have been achieved and then follwoed by a decline and demise are usually based on incomplete systems.

Institution or subsector analyses do not appear to be adequate bases for selection among various program alternatives within or among sectors. Criteria and measures which are broadly meaningful and which allow comparison of relative projects and programs must be developed. Intersectoral and sectoral analyses and planning should provide a fairly complete staging of inputs and outputs which permit tracing of actions and responsibilities through the system for rapid isolation of lagging elements and provision for timely remedial action. The full application of evaluation as a management tool is only possible within such a complete system. Effective management also requires that at each management level, the manager be able to view his own stage in relation to the stages that feed him inputs and those which are consumers of his outputs and to understand the overall relationships and implications of his actions. Flexibility must be built into the system to permit the manager to detect probable lags and shift resources intelligently to obtain essential outputs within the time limitations and to request and obtain additional resources or to alert managers at the appropriate levels of an anticipated lag so they can modify their targets or take other appropriate action.

This whole process then depends heavily upon a thorough understanding of the way the agricultural sector works, the internal and external mechanisms involved, the state of development and general health of the many interrelated components and the effects of policies and practices exercised by the government. A thorough sector analysis should provide this fundamental understanding upon which strategy and planning depend. Of all the functions carried out by assisting agencies in the developing countries, this one has received the least attention, yet no better method has been found for placing in perspective the entire complex of agricultural systems, to identify problems and plan corrective action at important points in the economy.

The general principles of how to conduct such analyses so as to achieve an unbiased and factual evaluation of the agricultural sector are now generally known and the techniques, methods and procedures for carrying out a sector analysis are now being better defined and more adequately structured.

The level of sophistication of a sector analysis can vary from quickie type studies of a few weeks' duration through more comprehensive analyses lasting a few months — at least through one cropping and marketing season — to one- or two-year very thorough and detailed studies made by a multidisciplinary team of experts assisting host country analysis teams. The ultimate is a never ceasing study that continuously upgrades and improves the analytical work, based on a constant stream of new data. The type analysis decided upon for any one study depends largely upon 1) the kinds of information needed for the level of strategy and planning contemplated, 2) the nature of commitments to be made based on the study, 3) the time available for the study - or the degree of urgency, 4) the number and competence of analysts that can be supplied by the host country, 5) the organizational structures from which these analysts are drawn, and 6) the funds available for the study. A very special problem exists particularly for small countries having inadequate numbers of trained analysts, no organized analytical institution, very little available funding and an urgent need for a sound planning base.

The developing countries ordinarily do not have adequate numbers of trained agricultural economists to carry ou sector analyses, identify the most useful development strategies, provide adequate planning, encourage helpful policy formulation, structure improved marketing systems and economic reseearch and to work with production specialists in improving efficiencies and profitability in farming systems. The problem of a low agricultural economics capability often prevents adequate analysis of LDC problems, allows poor choices among alternatives to go unnoticed, creates distortions in programs where interactions are critical and may make the selection of conditions precedent to sector loans difficult or awkward.

Simplified Systems

Many countries do not have the resources for, and may not really have the need for, highly sophisticated detailed studies and simulation models in order to do adequate planning. Yet failure to understand the agricultural system or the inability to adequately estimate the sensitivity of the system to specific changes in any of its parts, usually results in a hodgepodge of more or less unrelated projects, each in itself a good thing, but not adding up to an integrated program. Other such projects fails to achieve their individual goals because of other more limiting but undetected factors elsewhere in the system that prevented the expression of success in an otherwise good project. What is needed then is some kind of a simplified systems approach that is admittedly less than perfect but that would allow the planners to view the whole system at once so that a large number of variables and their interactions can be considered simultaneously. By such a system bottlenecks can be more readily identified, knowledge and action gaps surfaced, interactions estimated, institutional or organizational deficiencies pinpointed and alternate pathways considered. A very simple and highly generalized flow chart of such a system is included here, as Figure 1, that shows the central components of an agricultural system. This chart is a bare skeleton in that each block on the chart could be enlarged into a system of its own and other blocks added as required in specific cases, but a simplified form is adequate for this discussion.

Starting in the lower right-hand corner with the block labeled food needs (for this discussion, phrases or words underlined refer to items on the chart), we have a block that is easily calculated for any given country. All the data needed are the number of people in the population, the rate of pupulation growth and the amount of food considered to be an adequate diet for the region, and food needs can be readily determined. This number, arrived at in this way, is often frighteningly large and this is the number that has people and governments worried because it is larger than food production in many coutnries. It is often large enough to make most government officials reassess their doubts about Malthus. Now let's look at the next block labeled effective demand. This block represents the amount of food the population can afford to purchase — or it's a measure of the size of the market. Effective demand, particularly in a hungry country, is much smaller than food needs. Therefore, if farmers produce up to the need level and throw this production on a market (effective) that cannot absorb it, then this "over-production" works its way back through the system to farm prices. Farm prices fall, the incentive to produce is reduced and the farmer tends to retreat into subsistence agriculture because he has no other alternatives — and this is precisely what we are trying to get him out of. If consumer costs are held down by government policy (often done to maintain peace in the urban areas) the same thing happens to the farmer. That is, sooner or later, farm prices and farmers' profits decline and his production incentive goes down with it. If attempts are made to get farm prices up in order to increase production then this is eventually reflected in higher consumer prices which are politically explosive but worse than that, high consumer prices lower effective demand. This sets a ceiling on production more effectively than a lack of production technology. So we have a seesaw effect: trying to help the farmer and his incentives we hurt the consumer and demand. Trying to hold consumer costs down to get demand up we hurt the farmers' incentive. And we must have both — i.e., there must be a strong incentive to produce and a demand for the product, else production will not increase above subsistence levels.

One of the most workable ways to break this impasse is through the marketing process. There is usually a large spread between farm prices and consumer prices. If efficiencies can be achieved in the marketing process then large savings can be achieved in the price spread. If policies are such that a part of these savings can be allocated to the farmer and part to the consumer then incentive to produce and effective demand can be increased simultaneously. In the market block on the chart there is a list (illustrative but not all inclusive) of factors that can usually be improved. If market news can be made available to the farmer so that he knows the value of his commodity before he barters, if storage facilities are available for that production which cannot be sold immediately, if items can be processed for sale later, if distribution is faster and cheaper, if spoilage can be reduced, then the spread can be reduced. Middlemen, multiple transfers and sales taxes on transactions contribute to large price spreads and much can be gained by efforts to increase efficiency in this area. Paradoxically the middlemen -- shippers, warehousemen, wholesalers, retailers, etc. — are the only organized group in the marketing process. Farmers rarely know what prices the ultimate consumer pays and the consumer is usually not aware of what the farmer receives. The people who work in the price spread area are wonderfully adept at soaking up efficiencies achieved at either end of the marketing chain, i.e. if production costs are reduced, making lower commodity prices possible, this is rarely reflected in decreased consumer costs. Conversely, when consumers must pay higher prices to farmers, this almost never results in higher prices to farmers. Government intervention that would increase competition in the marketing area usually pays big dividends in farmer incentive and consumer demand, both prime requisites for increased production.

The Government block has been divided arbitrarily into a national government that sets policies and a local government that is more involved in local planning and organization. On the national government side, a single policy, guaranteed minimum prices, is used as an example only. Any one or group of policies could be included or substituted for this one. Guaranteed prices do not mean a subsidized nor necessarily a very high price. It is intended as a floor or minimum price. This reduces the farmer's marketing risks and gives him confidence to purchase the inputs required to get high yields. The problem with this procedure is that it is difficult to decide on which policies would give the best results and it is often difficult to get traditional policies changed even when they have become disincentives to investment in the agricultural sector. Many times policy changes are politically difficult for governments to make. Lending agencies usually write policy changes into loan requirements but often write in too many conditions or insist on policy changes that really do not have much effect. That is to say that until the lending agency has gained competence in estimating the sensitivity of the production system to various policy changes made to different degrees and at different times, they are not yet prepared to wisely write the conditions precedent to the loan. A systems approach should minimize this difficulty.

On the local government side, the most important factor assisting farm income is where private sector processors offer farmers contracts for their production, at prices agreed to prior to planting, if the farmers will meet processors' requirements for variety, quality, etc. This is already working well in many countries for certain products. The difficulty here is that the process usually is helpful only to those farmers near the processing plant. But the basic principle is no different than the government backed guaranteed minimum price program. Both of these should tend to raise farm income and production incentive.

The production block is where most assistance agencies have put major emphasis. Here we expect the private sector to provide cheaper inputs to farmers. This, added to the production technology coming from the experiment stations give higher yields at lower per unit cost of production. This gives increased farm profits without price changes. This process is a powerful tool in getting production incentives up without increasing consumer prices. The whole system then is geared to getting consumer demand up without reducing farmers' prices or getting farm prices up without killing off the demand, or some desirable mix of the two.

If the private sector earns profits selling inputs to farmers, and they must, then this is reflected in somebody's increased income which is a major factor in demand. Farm profits increase demand also, mainly for commodities other than food, but it is surprising how much processed food is now sold in many rural communities. So we have come full cycle on the chart. Now the problem is how do we get all of these blocks on stream at the same time. This is the basic strategy and when the system is working fairly well we expect:

1. Farm prices to improve
2. The incentive to produce to grow and production to increase
3. The price spread to decline
4. Consumer costs to decline or remain stable or at least to increase slower than income
5. Effective demand to get closer and closer to food needs — the basic goal.

Now, we come to a seeming paradox. Almost everywhere in the LDCs we encounter markets full of food. In the face of real hunger much food is for sale and it is mostly food of local production and it is almost never all sold. This means essentially that the farmer has always traditionally produced up to effective demand and he is still doing so today. Actually, because there is a large spoilage component in storage and in the wholesale and retail markets, the farmer is producing above effective demand, by the amount of this spoilage, minus imports. Anywhere you travel, even in remote villages, if you have some money you can buy food. It is very true, however, that if all of the people had enough money to buy all the food they wanted, the local markets would run out quickly, but there is nearly always enough food to satisfy effective demand. Farmers know that they only drive markets down when they produce more than they can sell, so any program that pushes increased production without getting demand up is likely to fail.

If the farmer has always met effective demand, how was this possible? Generally it has been possible because demand has always gone up slowly. Population growth and increased incomes both tend to make demand go up (and they are both occurring all over the world) but spiraling consumer prices depress it. The resultant vector is a very slow rise in demand and a primitive agriculture can change fast enough to meet this slow demand rise. Farmers have traditionally done this by increasing the land cultivated or, in their own limited way, increased the intensity of their agriculture. They have not generally gone the route of purchased inputs and high level technology where quantum jumps in production are possible basically because it has not been profitable. But they have about used up these two ways of increasing production. There may be more land but it is remote and not economically available to the farmers and they cannot intensify much more without resorting to high cost inputs of fertilizers, new varieties, pesticides, etc. Therefore, if effective demand for food should take off under the impetus of population growth and increased incomes, then a primitive agriculture would no longer be adequate and means would have to be found to make new lands available to the farmers or increase his profits to the point where he could afford technical inputs or some mix of the two.

The system then is like a heating system that pumps hot water to all the rooms in a house. It's a continuous system and any restriction anywhere in the house reduces the flow. The problem may be upstairs, downstairs, in front of the pump, behind the pump or in the furnace, but a restriction slows down the whole system. If it was a complete stoppage the limiting factor could readily be located, but it is rarely so in agricultural systems. Different parts of the system may work well or poorly at different times so a mechanism for locating bottlenecks that are not obviously apparent is necessary.

There is nothing really new in this system. All of the items have been discussed for years. This approach is simply an attempt to organize the major factors in such a way that the effects of each part and the possible interaction between parts becomes apparent. Analysis of the agricultural sector along these lines should show where major effort is required and should tend to concentrate resources on the most limiting factor. This is particularly important because usually there are not enough funds to work on all the various parts at once. As soon as the most limiting factor has been identified and progress is being made towards a solution to this particular problem, then attention can be directed at deciding which factor will become the most limiting once the first one has been solved. By this process an order of priority can be established.

Of copurse this chart must be altered to fit conditions in any specific country. In its present form it is so generalized that it may omit factors peculiar to a given country. For simplicity many factors have been omitted but are implied. Research must be applied at several points, particularly to production and marketing, extension activities fit between the production block and the farmer, land tenure problems could be attached as a policy problem, etc., until the chart fits the country of concern to the planner. This approach is simply a plea for orderly thinking about a food problem. It is no panacea nor is it a substitute for careful analysis, thoughtful strategy formulation and detailed planning. Rather it is a tool that should facilitate

A Proposed Development Sequence

A. Data	(What do we know? What are orders of magnitude? How are data collected? How reliable? Are there gaps?)
B. Analysis	(Where are we? What is the data trying to tell us? What does it really mean to people? What do we have to work with? What can we do?)
C. Goals, Objectives	(Where do we want to go? What are we trying to achieve? What is the purpose of outside help?)
D. Assessment	(Is C realistic? Overstated? Understated? Are there reasonable ways to get from B to C? Can they be financed? Administered?)
E. Essential Steps (Strategy)	(What are the major things needed to be done to reach C?)
F. Planning	(What are workable methods and means? What kind of a plan is needed to accomplish E? 1. Is it technically possible? 2. Is it economically feasible? 3. Is it politically acceptable? 4. Is it administratively practical? 5. Is it socially desirable?)
G. Organization	(How do we set up a system to make A through F a continuous operation and to accomplish E by carrying out F?)
H. Implementation	(Put F in motion, administered by G)
I. Evaluation	(Is H going ahead? Are G and F working? Are we headed towards E? Will this lead us to C in a reasonable time frame?)
J. Feedback	(Have I revealed errors or indicated a waste of resources which we do not want to repeat? Or success we do want to repeat? Feed back I information to A through H to upgrade system)

Estimating Return Periods for Extreme Events

Ken Vogler

Watershed management often involves the design and construction of flood control structures and soil and water conservation works. The size of structures or works must be economically feasible and should be designed to handle safely extreme events. Thus, it is necessary to estimate the magnitude of a hydrologic event, such as runoff volume or peak flow, that can be expected to equal or exceed the design of the structure at least once during its projected lifetime.

These extreme events are analyzed using probability distributions as models and are often classified in terms of a return period. The return period has been defined as the average interval in years between events which equal or exceed the considered magnitude of the event. Return periods are determined for many hydrologic processes including rainfall depth, rainfall intensity, runoff volume and peak flow.

Extreme event data is often considered in two ways, as an annual series and as a partial series. The annual series are those data which consist of the peak value for any particular year. The partial series consists of those data which exceed a certain base value, regardless of the number of times that base is exceeded in a year. The annual series is advantageous because most hydrologic data is processed in a way which makes it easy to get peak annual events and a good theoretical basis has been established for extrapolation of peak annual events. A principle argument against annual series is that it does not consider large events which are not peak annual events. On the other hand partial series considers all events above a base level. Because of the lack of independence that can occur between events, a good statistical theory has not yet been developed for partial series. Partial series does give larger values for lower return periods than does annual series; however, both give essentially the same values for return periods greater than ten years.

In this paper, the annual series will be considered for which the Gumbel Extreme Value Distribution has been found to fit observed data very well. Often extreme value data will not fit a Gumbel distribution and other distributions such as the Log Pearson Type III should be considered.

A graphical technique is used in which observed data are plotted on Gumbel graph paper and the magnitude of the event is simply read off the graph for the desired return period. If the mean and mode of the data are known, then these points can be plotted on Gumbel paper and used to draw a straight line which also represents the relationship between magnitude and return period. Opinion is currently divided as to which of these two methods is preferable.

Procedure

Annual peak values are chosen for a given hydrologic process, i.e., rainfall depth/event, daily rainfall depth, average daily discharge or instantaneous peak discharge, for a data record of at least thirty years. Peak values are ranked in increasing order and assigned a number starting with one for the smallest event. The relative frequency is estimated as:

$$f = m/(n + 1)$$

where f = frequency of occurrence
m = rank assigned to the peak value
n = number of years of record.

The relative frequency is then plotted with the corresponding peak annual value on Gumbel paper. A straight line is fitted to the plotted points by "eyeballing" and the values for peak annual events are then read for a given return period or probability of occurrence.

Example

This example compares peak annual instantaneous runoff values fitted to the Gumbel and the Log Pearson Type III distributions. Thirty-six years of data from the Sabino Creek Basin near Tucson, Arizona are used. In this case, the Log Pearson distribution gives a better fit. A discharge of 4690 cfs is expected for a return period of 25 years using this distribution. On the other hand it is difficult to determine what the discharge will be from the Gumbel distribution because of the wide variation between the eyeballed line and the statistical line (5,150 and 3,600 cfs respectively).

Sabino Creek

To determine the number of intervals in a histogram

$K = 1 + 3.3 \log n$

where n = number of years of record

$K = 6$

interval in cfs	no. of occurences
0 - 1000	18
1001 - 2000	8
2001 - 3000	5
3001 - 4000	2
4001 - 5000	1
5001 - 6000	2

Mode	500
Mean	1527.0
Var.	1977804
SD.	1406

Sabino Creek

Statistical Parameters for Log Pearson Type III

log mean = 2.999
log s = 0.435
log coef. skew = ⁻0.556105
log Q = log Ma + K (log σ_Q)

Recurrence years	% chance	K interpolated	log Q	Q
2	50	0.092	3.03902	1,094
5	20	0.857	3.371795	2,354
10	10	1.207	3.524045	3,342
25	4	1.545	3.671075	4,689
50	2	1.745	3.758075	5,729
100	1	1.913	3.831155	6,779
200	0.5	2.056	3.89336	7,823
1000	0.1	2.330	4.01255	10,293

Formulas used

$$\text{mean} = \frac{1}{N}\sum_{i=1}^{N} X_i \qquad S = \frac{1}{N-1}\sum_{i=1}^{N}(X_i - \bar{X})^2$$

$$\text{Coefficient of Skew } (g) = \frac{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^3}{S^3}$$

Values for K are determined from Tables of Skew Curve Factors for the Log Pearson Type III distribution using g.

Sabino Creek near Tucson, Arizona
Drainage area 35.5 sq. miles
Gila River Basin
Water year October - September

Year	Discharge cfs	Year	Discharge cfs
1933	510	1951	750
1934	472	1952	1,640
1935	540	1953	861
1936	500	1954	5,110
1937	2,020	1955	2,000
1938	3,200	1956	55
1939	385	1957	2,030
1940	904	1958	1,500
1941	3,180	1959	4,240
1942	449	1960	1,600
1943	567	1961	910
1944	175	1962	1,010
1945	916	1963	2,070
1946	2,000	1964	1,310
1947	227	1965	244
1948	380	1966	6,400
1949	1,430	1967	788
1950	2,260	1968	2,340

from Water Resources Data for Arizona

Sabino Creek

Rank	Discharge	Cumulative Frequency	Logged Values
1	55	0.0270	1.740
2	175	0.0541	2.243
3	227	0.0811	2.356
4	244	0.1081	2.387
5	380	0.1351	2.580
6	385	0.1622	2.585
7	449	0.1892	2.652
8	472	0.2162	2.674
9	500	0.2432	2.699
10	510	0.2703	2.708
11	540	0.2973	2.732
12	567	0.3243	2.754
13	750	0.3514	2.875
14	788	0.3784	2.897
15	861	0.4054	2.935
16	904	0.4324	2.956
17	910	0.4595	2.959
18	916	0.4865	2.962
19	1,010	0.5135	3.004
20	1,310	0.5405	3.117
21	1,430	0.5676	3.155
22	1,500	0.5946	3.176
23	1,600	0.6216	3.204
24	1,640	0.6486	3.215
25	2,000	0.6757	3.301
26	2,000	0.7027	3.301
27	2,020	0.7297	3.305
28	2,030	0.7568	3.307
29	2,070	0.7838	3.316
30	2,260	0.8108	3.354
31	2,340	0.8378	3.369
32	3,180	0.8649	3.502
33	3,200	0.8919	3.505
34	4,240	0.9189	3.627
35	5,110	0.9459	3.708
36	6,400	0.9730	3.806

Predicting Soil Loss

J. L. Thames and J. M. Kramer

At present the Universal Soil Loss Equation (USLE) is the model most often used to predict soil losses. Especially in the U.S., the equation has been adopted by the Soil Conservation Service (SCS) for work concerned with areal erosion. For many years the equation, developed by Wischmeier and his associates from 1957 onwards (i.e., Wischmeier and Smith, 1965; Wischmeier and Smith, 1978), has been used on agricultural lands, from 1971 on construction sites and from 1972 onwards also for range and forest lands. Correlations have been satisfactory for conditions in North America, but the equation may not always apply in other environments. For instance, the rainfall factor (R) has a high correlation with soil loss on Java, Indonesia, but a poor correlation with soil loss in Benin. Therefore, the equations may need to be adapted to local conditions, especially the significance of the rainfall factor (R) and the cropping-management factor (C). Also, although the USLE equation is a simple steady-state model, it requires a rather sophisticated data set, especially with respect to rainfall (daily records over a number of years), vegetation, and, to a lesser extent, soil conditions. Even when sufficient data are available some caution is needed because little experience has been gained on slopes over 20° or longer than 150 m (500 ft).

This section is mainly based upon Wischmeier and Smith, Agriculture Handbook No. 282, Arnoldus, 1977.

The Basic Equation

The basic equation is

$$A = R \times K \times LS \times C \times P$$

and is written as

$$A = R\ K\ L\ S\ C\ P \qquad (1)$$

in which

A = computed soil loss per unit area; obtained by multiplication of the remaining factors.

R = rainfall factor; the number of erosion index units (EI - units) in the period of consideration. The erosion index is a measure of the erosive force of raindrop impact.

K = soil erodibility factor; the erosion rate per unit of erosion index for a specific soil, in a cultivated continuous fallow on a 9 percent slope, 22.1 m (72.6 ft) long.

L = slope length factor; the ratio of soil loss from the field slope length to that from a 22.1 m (72.6 ft) length on the same soil type and gradient.

S = slope gradient factor; the ratio of soil loss from the field gradient to that from a 9 percent slope, on the same soil type and slope length.

C = cropping-management factor; the ratio of soil loss from a field with specific cropping and management to that from the fallow condition on which the factor K is evaluated.

P = erosion-control practice factor; the ratio of soil loss with contouring, stripcropping or terracing etc., to that with straight-row farming, up-and-down slope.

Evaluation of the Factors: the USLE has been developed in the pound-foot-second system. In this presentation both metric-units (m-units) as well as pound-foot-second units (pfs-units) will be given, the latter between brackets.

Rainfall factor R

In order to arrive at the total kinetic energy (E), the precipitation is divided into periods with approximately the same rainfall intensity. For each period with the same rainfall intensity, the kinetic energy is calculated according to:

$E = 210.2 + 89 \text{ Log } I$ (joules/m^2 per cm of rain)
$E = 916 + 331 \text{ Log } I$ (foot-tons/acre per inch of rain)

I= rainfall intensity of the considered period in cm/hr [inches/hr].

Tables have also been developed (Wischmeier and Smith, 1958) from which the kinetic energy can be read. These tables are given as Table 1a (in m-units) and Table 1b (in pfs-units).

To obtain the total kinetic energy of a storm, the kinetic energy calculated for each period is multiplied by the cm [inches] of rain that fell during that period. These products are then summed.

To obtain the R-value the total kintic energy of a storm is multiplied by twice the maximum average 30-minute intensity (I_{30}) and divided by 100. The maximum 30-minute intensity can be obtained from a recording raingauge chart. The I_{30} is multiplied by two in order to convert intensity/0.5 hr into intensity/hr.

Soil erodibility factor (K)

Erodibility is the vulnerability or susceptibilty of the soil to erosion. It is determined by the physical properties of the soil: (1) those that affect the infiltration rate, permeability and total water capacity, (2) those that resist the dispersion, splashing, abrasion and transporting forces of the rainfall and runoff. The key to developing a reliable estimate of K lies in understanding the influence of particle-size interrelations on soil erodibilty.

A standard soil loss/runoff plot has been defined against which field values for the factors can be compared. It is 22.1 m (72.6 ft) long with a uniform lengthwise slope of 9 percent, in continuous fallow, tilled up and down slope.

The soil erodibilty factor can be evaluated on experimental plots by solving the equation:

$K = A/RLSCP$ for the general case, or
$K = A/R$ for standard conditions.

A nomograph has been devised (Wischmeier et al, 1971) that enables evaluation of the K value from five simple soil parameters:

1) Percent silt and very fine sand (0.002 - 0.10mm particle size).

2) Percent sand [0.10 - 2.0mm].
3) Percent organic material.
4) Structure.
5) Permeability.

The values for percent silt and very fine sand, percent sand, percent organic material and structure are values for the upper 15 - 20cm [6 - 7in]. The values for permeability refer to the profile as a whole.

Particle size

Particle size is a major determinate of soil erodibilty. To improve the predictive value of the two parameters they have been slightly redefined. Silt is considered to include very fine sand and the sand size range is somewhat reduced. The particle-size parameter is then defined as the product of percent silt and percent sand and silt.

Organic material

It has been found that organic material in the range 0–4 percent is inversely related to erodibilty and that the magnitude of this effect is related to texture (Wischmeier et al., 1971). The curve that relates percent organic material to erodibility is included in the nomograph. In part it explains the difference between topsoil and subsoil erodibilty, the latter having a reduced OM fraction.

Soil structure

Structure type and size, but not grade, are important in determining erodibility. Structure is coded as:

1) Very fine granular and very fine crumb (<1mm).
2) Fine granular and fine crumb (1-2mm).
3) Medium granular, medium crumb (2-5mm).
4) Platy prismatic, columnar, blocky and very coarse granular.

Soil permeability

Soil permeability classes are designed to be deduced from routine soil profile descriptions. A certain amount of flexibility in the system allows for experienced interpretations of specific soil profiles. The basic classes, however, are sufficient for most field uses. They are coded as:

1) Rapid to very rapid.
2) Moderately rapid.
3) Moderate.
4) Moderately slow.
5) Slow.
6) Very slow.

General permeablity classes guides are given in the USDA Soil Survey Manual (Soil Survey Staff, 1951), but laboratory determinations are not necessary in general. They supplemented the guides with the following rules of thumb for codes 4, 5 and 6:

- fragipan soils are coded 6;
- more permeable surface soils underlain by massive clay or silty clay are coded 5;
- moderately permeable surface soils underlain by a silty clay or silty clay loam having a weak subangular or angular blocky structure are coded 4;
- if the subsoil structure grade remains moderate or strong, or the texture remains coarser than silty clay loam, the code is 3.

Calculation of K-factor

The procedure for evaluating the K-factor with the use of the nomograph (Figure 1) is as follows:

1) Enter the nomograph on the vertical scale at the left with the appropriate percentage silt + very fine sand (0.002 mm - 0.10 mm).

2) Proceed horizontally to intersect the correct percent-sand curve (0.10 mm - 2.0 mm), interpolating to the nearest percent.

3) Proceed vertically to the correct organic matter content.

4) Proceed horizontally to the right.

5) For soils with a fine granular or fine crumb structure and moderate permeability the value of K can be read directly from the first-approximation of K scale on the right hand edge of the first section of the nomograph (only in metric units).

6) For all other soils: continue horizontally to intersect the correct structure curve.

7) Proceed vertically to the correct permeability curve.

8) Proceed horizontally to the soil-erodibility scale on the left hand edge of the second section of the nomograph to read the value of K.

Experience with the nomograph in the U.S. led to the following additional recommendations (SCS, 1973):

1) K-values derived from the nomograph range from 0.03 [0.02 in pfs units] to 1.10 [0.69 in pfs units]. For practical purposes it suffices to use K-value classes, namely: 0.13; 0.19; 0.22; 0.26; 0.31; 0.36; 0.41; 0.48; 0.56; 0.63; 0.71; 0.83; [in pfs units: 0.10; 0.15; 0.17; 0.20; 0.24; 0.28; 0.32; 0.37; 0.43; 0.49; 0.55; 0.64.

2) K-values must be adjusted for coarse fragments if present. K-values for soils high in coarse fragments (gravelly, channery, shaly, slaty, cherty, cobbly, stony, or flaggy — for the definitions see USDA Soil Survey Manual, 1951, pp. 215, 216.) are reduced by one or two classes. K-values for soils that are very high in these coarse fragments are reduced by two or three classes.

3) In arid or semi-arid areas where erosion pavement is a significant factor in reducing soil loss the K value should be reduced by 33 percent if the soil is stony and by 50 percent if it is very stony.

Slope length factor (L) and slope gradient factor (S)

Slope length is defined as "The distance from the point of origin of overland flow to either of the following, whichever is limiting for the major part of the area under considerations: (i) the point where the slope decreases to the extent that deposition begins, or (ii) the point where runoff enters a well defined channel that may be part of a drainage network or a constructed channel such as a terrace of diversion" (Wischmeier, 1965).

The slope length factor is defined as:

$$L = (\vartheta/22.1)^m \qquad \text{(m)} \qquad \text{or as}$$
$$L = (\vartheta/72.6)^m \qquad \text{(pfs)}$$

where: ϑ = field slope length (meters, feet)
m = exponent, influenced by the interaction of slope length with gradient and may also be influenced by soil properties, type of vegetation, etc.

The exponent value ranges from 0.3 for very long slopes with a gradient of less than 0.5% to 0.6 for slopes over 10%. The average value, applicable to most cases is 0.5, the value used for the development of the slope-effect chart (Figure 2). The slope-effect chart allows one to read a value for the combined effect of slope length and slope gradient. Figure 3 allows one to use this chart in cases where values for the exponent other than 0.5 are more appropriate. The figure translates the field slope length for slopes with exponents $m = 0.3$, $m = 0.4$ and $m = 0.6$ into equivalent slope length with exponent $m = 0.5$.

The slope gradient factor is defined as:

$$S = (0.43 + 0.30s + 0.043s^2)/6.613$$

where: s = slope gradient (in %)

For slopes up to 20% and 350 m [1,148 ft] long the combined effect for slope length and slope gradient can be read from Figure 4. For slopes from 10% up to 50% and up to 800 m [2,625 ft] long, a rough estimation may be obtained from Figure 5, but the relationship has not been sufficiently tested to indicate the reliability of the prediction.

Foster and Wischmeier (1974) have adapted the LS factor for use on irregular slopes. This is especially useful on wildland sites which rarely have uniform slopes. They describe the combined factor as:

$$LS = \frac{\sum_{j=1} (s_j \lambda_j^{1.5} - s_j \lambda_{j-1}}{\lambda_e (72.6)^{0.5}} \qquad \text{pfs}$$

where: λ_j = distance in feet from the top of the slope to the lower end of the jth segment.
λ_{j-1} = the slope length above segment j.
λ_e = overall slope length.
S_j = S factor for segment j.

The graph in Figure 6 can be used in place of the equation. The graph is a family of curves, for specified slopes ranging from 2% to 20%. The quantity $(S\lambda^{1.5}/72.6^{0.5})$ is designated by the symbol μ and is plotted on Log-Log paper against the values of λ. The graph is entered on the horizontal axis with the value of μ_r. Moving upwards to the curve for the percent slope for the segment j, the value of μ_{1j} is read on the vertical scale. The graph is then entered with the value of λ_j to obtain the corresponding value of μ_{2j}. The difference then equals the quantity,

This procedure is repeated for each of the slope segments, and the n values of $(\mu_{2j}-\mu_{1j})$ are summed. Dividing the sum by the overall slope length λ_e gives the effective LS value determined by this procedure is a function of all the segment lengths and slope steepnesses and also of their particular sequence on the slope.

The percentage of the total sediment yield that comes from each of the n segments is also obtained by this computational procedure. The relative sediment contribution of any segment j is:

$$\mu_{2j} - \mu_{1j} \Big/ \sum_{j=1}^{n} (\mu_{2j} - \mu_{1j})$$

Cropping management factor (C)

This factor describes the total effect of vegetation, residue, soil surface and land management on soil loss. The value of the factor is in most casen not constant over the year. Although treated as an independent vnriable in the eqnation, the "true" value of this factor is probably dependent upon all other factors. Therefore, the value of the C-factor needs to be estabnished experimentally in many cases.

For crops: C-values need to be established for each of the following stages for all crops of the rotation (11):

period F: rough fallow (turn ploughing to seeding);

period 1: seeding (seedbed preparation to 1 month after planting);

period 2: establishment (from 1 to 2 months after spring or summer seeding; for fall seeded grain this period includes the winter months);

period 3: growing and maturing crops from the end of period 2 to crop harvest;

period 4 residue or stubble.

It should pointed out that the value found for a period F in the rotation cannot be extrapolated to any other fallow periods within the rotation, because the value is influenced by the cropping history of the soil, the nature and quantity of residue turned under and other factors.

In order to arrive at a proper value for a crop rotation the soil loss ratio (i.e. the ratio of soil loss from the field with the particular cropping and management to that of bare soil) has to be adjusted according to the distribution of the erosion-index for each period, because field conditions are immaterial when there is no rain and most important when there is much rain. Therefore the soil loss ratio for each period is multiplied with the percentage of EI^{30}-index applicable to that period. This percentage of EI_{30}-index can easily be read from an erosion-index distribution curve (see Arnoldus, 1977). Tables have been developed from which the soil loss ratios for the different periods of the common rotations can be read. In combination with the appropriate erosion-index distribution curve, the C-value for any part of the rotation can be established. This table and the distribution curves are presented in Agriculture Handbook No. 537 (Wischmeier and Smith, 1978).

In areas of the world for which no guidelines for the establishment of C-values for field-crop exist, it is probably easiest to try to correlate soil loss ratio with amount of dry organic matter per unit area or with percent ground cover.

For permanent pasture, range lands and idle lands and for woodlands, tables have been published (SCS, 1975) from which the averge annual C-values can be read. These tables are reproduced as Tables 2 and 3.

Non-agricultural C factors

The C-factor portion of the equation is currently being modified to better express forest management conditions. Nine elements have been selected that should be considered when developing this factor for woodlands. The following is a summary of the elements based on that of Dissmeyer (1978).

Eight of the nine elements have been used in the development of the agricultural C-Factors, only a few of which have been published. One new element has been developed for forest land that does not occur in the agricultural environment — namely the step element.

The nine elements are soil consolidation, surface residue, canopy, fine roots, residual effect of fine roots after tillage, contour effect, roughness, weeds and grasses, and steps. Surface residue is the effect of the area covered by litter, slash and live vegetation, which is the predominant factor. The other eight factors are evaluation or modification of the influence of bare ground.

Soil consolidation can be viewed as a modifier of the basic erosion factor (K-Factor). The K-factor as published is for continuously tilled soil, in fallow condition with tillage up and down the slope. Tillage breaks down soil structure, aggregates, bonds, etc., which leaves the soil more erodible than untilled soils. Research has found that if fallow plots are left untilled, the erosion rate reduces over time until seven years have past where no further erosion reduction occurs. At this point, the erosion rate is 45% of that of the original fallow conditions. For forest soils the soil consolidation modifier of 0.45 is used. If the soil is tilled by bedding, discing, etc., the K-Factor is modified by a soil consolidation factor which is a function of time since tillage.

Surface residue (that is, litter, slash, logs, rock, live vegetation, etc.) in direct contact with the soil surface is the first element to evaluate. The percent area occupied by surface residue is projected into a chart to derive the factor.

The following elements plus soil consolidation apply to the bare ground only, so we focus our attention now to the exposed soil and its condition.

Canopy cover (litter, slash, logs, rock, live vegetation, etc.) in direct contact with the soil surface is the first element to evaluate. The percent area occupied by surface residue is projected into a chart to derive the factor.

Fine roots in the top one or two inches of soil are very important in tying soil particles together. These fine roots are the feeding roots of trees, grasses etc. The element is evaluated by inspecting the bare area and estimating the percent area with fine roots and projecting onto a graph. Fine roots usually have to be physically removed by scalping or pushing the soil with a dozer or tractor. This element is only used for non-tilled areas. If the area has been tilled thus cutting up this mat of fine roots, another element is used — residual effects of fine roots after tillage. This is read from a chart with a correction for time elapsed since last tilled.

If an area has been tilled, invading weeds and grasses, and sprouting are assumed to compensate for decaying fine roots, thus avoiding double counting.

Contour tillage can reduce erosion and this element is used on disced and bedded areas. The contour element is a function of slope and alignment of the furrow within the contour. As slope increases the effect from this element decreases and as the alignment increasingly departs from the contour, the effect decreases. This element is estimated by using a table, a chart and a simple equation.

Roughness expresses the influence of surface depression storage available to trap on-site soil movement. This factor is estimated in the field.

Finally, the step element expresses the influence of small steps that form on hillsides as a result of on-site erosion and deposition process. Close examination of the soil surface will often reveal a fairly large percent of the area in small steps. The element is a function of slope and of the percent area in steps. It is evaluated with the use of a chart.

The computation of the C-Factor is the simple multiplication of pertinent element factors for the disturbance.

Erosion-control practice factor (P)

The effect of erosion-control measures is considered an independent variable, therefore it has not been included in the cropping management factor. The soil loss ratios for erosion-control practices vary according to slope gradient. Soil loss ratios for contouring, contour strip cropping and terracing are given in Table 4. In the table, two values are presented for terracing: the higher one describes the soil loss from the field, the lower one the effect on sedimment yield, the difference being the sediment lost from the field but trapped in the terrace channel.

Soil Loss and Conservation Planning

For conservation planning the soil loss tolerance (T)(i.e., the maximum soil loss that can be tolerated) needs to be established. The following guidelines are used in the U.S.A. (SCS, 1974).

Soil loss tolerance (T), sometimes called permissible soil loss, is the maximum rate of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely.

Soil loss tolerance values (T) of 2.3 through 11.2 tons per hectare per year (1 to 5 tons/acre per year) are used. The numbers represent the permissible soil loss where food, feed and fiber plants are to be grown. "T" values are not applicable to construction sites but can be used on forest and wildland sites.

A single T value is normally assigned to each soil series. A second T-value may be assigned to certain kinds of soil where erosion has significantly reduced the thickness of the effective root zone, thus reducing the potential of the soil to produce plants over an extended period of time. For example, eroded phases of soil series that are shallow to moderately deep to a soil layer that restricts roots are commonly given a T-value one class lower than the uneroded phase of the same soil. The following criteria are used by soil scientists and other specialists for assigning soil loss tolerance values (T) to soil series:

(1) An adequate rooting depth must be maintained in the soil for plant growth. For soils that are shallow over hard rock or other restrictive layers, it is important to retain the remaining soil; therefore, not much soil loss is tolerated. The soil loss tolerance should be less on shallow soils or those with impervious layers than for soils with good soil depth or for soils with favorable underlying soil materials that can be renewed by management practices (Table 5).

(1) Soils that have significant yield reductions when the surface layer is removed by erosion are given lower soil loss tolerance values than those where erosion effects yield very little.

A maximum of 11.2 tons of soil loss per ha per year has been selected for use with the universal soil loss equation. This maximum value has been used for the following reasons:

1) Soil losses in excess of 11.2 tons per ha per year affect the maintenance, cost and effectiveness of water-control structures such as open ditches, ponds, and other structures affected by sediment.

2) Excessive sheet erosion is accompanied by gully formation in many places causing added problems to tillage operations and to sedimentation of ditches, streams and waterways.

3) Loss of plant nutrients. The average value of nitrogen and phosphorus in a ton of soil is about two to three dollars. Plant nutrient losses of more than twenty five dollars per ha per year is considered to be excessive. (Monetary values are estimates from 1973.)

4) Numerous practices are known that can be used successfully to keep soil losses below maximum tolerable levels.

After having established the soil loss tolerance we can rewrite the USLE as:

$$CP = T / RKLS$$

By choosing the right cropping management system and appropriate conservation practices, a value for the combined effect of C and P can be established that fits the equation. In order to do so it will be helpful to consult the erosion-index distribution curve of the area in order to single out the most critical stages as far as rainfall agressivity is concerned, because these are the stages where improvements result in the greatest reduction in the C-value.

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TABLE 1.a: KINETIC ENERGY OF NON-OROGRAPHIC RAIN
(Part 1) (Joules/m^2 per cm of rain)

Intensity cm/hr	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0.0	0.00	32.3	59.09	74.76	85.88	94.51	101.56	107.51	112.68	117.23
0.1	121.30	124.98	128.35	131.44	134.31	136.97	139.47	141.81	144.02	146.11
0.2	148.09	149.98	151.78	153.49	155.14	156.72	158.23	159.69	161.10	162.45
0.3	163.76	165.03	166.26	167.45	168.60	169.72	170.81	171.87	172.90	173.91
0.4	174.88	175.84	176.77	177.68	178.57	179.44	180.29	181.12	181.93	182.73
0.5	183.51	184.27	185.02	185.76	186.48	187.19	187.89	188.57	189.25	189.91
0.6	190.56	191.19	191.82	192.44	193.05	193.65	194.24	194.82	195.39	195.96
0.7	196.51	197.06	197.60	198.14	198.66	199.18	199.69	200.20	200.70	201.19
0.8	201.68	202.16	202.63	203.10	203.56	204.02	204.47	204.92	205.36	205.80
0.9	206.23	206.66	207.08	207.50	207.91	208.32	208.72	209.12	209.52	209.91
1.0	210.30	210.69	211.07	211.44	211.82	212.19	212.55	212.92	213.28	213.63
1.1	213.98	214.33	214.68	215.02	215.37	215.70	216.04	216.37	216.70	217.02
1.2	217.35	217.67	217.99	218.30	218.62	218.93	219.23	219.54	219.84	220.14
1.3	220.44	220.74	221.03	221.32	221.61	221.90	222.19	222.47	222.75	223.03
1.4	223.31	223.58	223.85	224.13	224.39	224.66	224.93	225.19	225.45	225.71
1.5	225.97	226.23	226.48	226.74	226.99	227.24	227.49	227.74	227.98	228.22
1.6	228.47	228.71	228.95	229.19	229.42	229.65	229.89	230.12	230.35	230.58
1.7	230.81	231.04	231.26	231.49	231.71	231.93	232.15	232.37	232.59	232.80
1.8	233.02	233.23	233.45	233.66	233.87	234.08	234.29	234.49	234.70	234.91
1.9	235.11	235.31	235.51	235.72	235.91	236.11	236.31	236.51	236.70	236.90
2.0	237.09	237.28	237.48	237.67	237.86	238.05	238.23	238.42	238.61	238.79
2.1	238.98	239.16	239.34	239.53	239.71	239.89	240.07	240.25	240.42	240.60
2.2	240.78	240.95	241.13	241.30	241.47	241.64	241.82	241.99	242.16	242.33
2.3	242.49	242.66	242.83	243.00	243.16	243.33	243.49	243.65	243.82	243.98
2.4	244.14	244.30	244.46	244.62	244.78	244.94	245.09	245.25	245.41	245.56
2.5	245.72	245.87	246.02	246.18	246.33	246.48	246.63	246.78	246.93	247.08
2.6	247.23	247.38	247.53	247.68	247.82	247.97	248.12	248.26	248.40	248.54
2.7	248.69	248.83	248.98	249.12	249.26	249.40	249.54	249.68	249.82	249.96
2.8	250.10	250.24	250.37	250.51	250.65	250.78	250.92	251.05	251.19	251.32
2.9	251.45	251.59	251.72	251.85	251.98	252.11	252.25	252.38	252.51	252.64

TABLE 1.a: (Part 2)

Intensity cm/hr	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
3	252.76	254.03	255.26	256.45	257.60	258.72	259.81	260.87	261.90	262.91
4	263.88	264.84	265.77	266.68	267.57	268.44	269.29	270.12	270.93	271.73
5	272.51	273.27	274.02	274.76	275.48	276.19	276.89	277.57	278.25	278.91
6	279.56	280.19	280.82	281.44	282.05	282.65	283.24	283.82	284.39	284.96
7	285.51	286.06	286.60	287.14	287.66	288.18	288.69	289.20	289.70	290.19
8	290.68	291.16	291.63	292.10	292.56	293.02	293.47	293.92	294.36	294.80
9	295.23	295.66	296.08	296.50	296.91	297.32	297.72	298.12	298.52	298.91
10	299.30	299.69	300.07	300.44	300.82	301.19	301.55	301.92	302.28	302.63
11	302.98	303.33	303.68	304.02	304.37	304.70	305.04	305.37	305.70	306.02
12	306.35	306.67	306.99	307.30	307.62	307.93	308.23	308.54	308.84	309.14
13	309.44	309.74	310.03	310.32	310.61	310.90	311.19	311.47	311.75	312.03
14	312.31	312.58	312.85	313.13	313.39	313.66	313.93	314.19	314.45	314.71
15	314.97	315.23	315.48	315.74	315.99	316.24	316.49	316.74	316.98	317.22
16	317.47	317.71	317.95	318.19	318.42	318.66	318.89	319.12	319.35	319.58
17	319.81	320.04	320.26	320.49	320.71	320.93	321.15	321.37	321.59	321.80
18	322.02	322.23	322.45	322.66	322.87	323.08	323.29	323.49	323.70	323.91
19	324.11	324.31	324.51	324.72	324.91	325.11	325.31	325.51	325.70	325.90
20	326.09	326.28	326.48	326.67	326.86	327.05	327.23	327.42	327.61	327.79
21	327.98	328.16	328.34	328.53	328.71	328.89	329.07	329.25	329.42	329.60
22	329.78	329.95	330.13	330.30	330.47	330.64	330.82	330.99	331.16	331.33
23	331.49	331.66	331.83	332.00	332.16	332.33	332.49	332.65	332.82	332.98
24	333.14	333.30	333.46	333.62	333.78	333.94	334.09	334.25	334.41	334.56

TABLE 1,b: KINETIC ENERGY OF NON-OROGRAPHIC RAIN
(Foot-tons/acre per inch of rain)

Intensity in/hr	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0	254	354	412	453	485	512	534	553	570
0.1	585	599	611	623	633	643	653	661	669	677
0.2	685	692	698	705	711	717	722	728	733	738
0.3	743	748	752	757	761	765	769	773	777	781
0.4	784	788	791	795	798	801	804	807	810	814
0.5	816	819	822	825	827	830	833	835	838	840
0.6	843	845	847	850	852	854	856	858	861	863
0.7	865	867	869	871	873	875	877	878	880	882
0.8	884	886	887	889	891	893	894	895	898	899
0.9	901	902	904	906	907	909	910	912	913	915
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	916	930	942	954	964	974	984	992	1000	1008
2	1016	1023	1029	1036	1042	1048	1053	1059	1064	1069
3	1074	1079	1083	1088	1092	1096	1100	1104	1108	1112
4	1115	1119	1122	1126	1129	1132	1135	1138	1141	1144
5	1147	1150	1153	1156	1158	1161	1164	1166	1169	1171
6	1174	1176	1178	1181	1183	1185	1187	1189	1192	1194
7	1196	1198	1200	1202	1204	1206	1208	1209	1211	1213
8	1215	1217	1218	1220	1222	1224	1225	1227	1229	1230
9	1232	1233	1235	1237	1238	1240	1241	1243	1244	1246

TABLE 2: "C" Values for Permanent Pasture, Rangeland, and Idle Land[a]

Vegetal Canopy			Cover That Contacts the Surface					
Type and Height of Raised Canopy[b]	Canopy Cover[c] %	Type[d]	Percent Ground Cover					
			0	20	40	60	80	95-100
Column No.:	2	3	4	5	6	7	8	9
No appreciable canopy		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.090	.043	.011
Canopy of tall weeds or short brush (0.5 m fall ht.)	25	G	.36	.17	.09	.038	.012	.003
		W	.36	.20	.13	.082	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.075	.039	.011
	75	G	.17	.10	.06	.031	.011	.003
		W	.17	.12	.09	.067	.038	.011
Appreciable brush or bushes (2 m fall ht.)	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.085	.042	.011
	50	G	.34	.16	.085	.038	.012	.003
		W	.34	.19	.13	.081	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.077	.040	.011
Trees but no appreciable low brush (4 m fall ht.)	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.087	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.085	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.083	.041	.011

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a/ All values shown assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists.

b/ Average fall height of waterdrops from canopy to soil surface: m = meters.

c/ Portion of total-area surface that would be hidden from view by canopy in a vertical projection, (a bird's-eye view).

d/ G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 5cm (2 inches) deep.

W: Cover at surface is mostly broadleaf herbaceous plants (as weeds) with little lateral-root network near the surface, and/or undecayed residue.

(This Table appeared as Table 1 in SCS, [illegible]).

Table 3 - "C" Factors for Woodland

(This Table appeared as Table 2 in SCS,1972, p.3)

Stand Condition	Tree Canopy a/ % of Area	Forest Litter b/ % of Area	Undergrowth c/	"C" Factor
Well stocked	100-75	100-90	Managed d/	.001
			Unmanaged d/	.003-011
Medium stocked	70-40	85-75	Managed	.002-.004
			Unmanaged	.01-.04
Poorly stocked	35-20	70-40	Managed	.003-.009
			Unmanaged	.02-.09 e/

a/ When tree canopy is less than 20%, the area will be considered as grassland, or cropland for estimating soil loss. See Table 2.

b/ Forest litter is assumed to be at least two inches deep over the percent ground surface area covered.

c/ Undergrowth is defined as shrubs, weeds, grasses, vines, etc. on the surface area not protected by forest litter. Usually found under canopy openings.

d/ Managed - grazing and fires are controlled.
Unmanaged - stands that are overgrazed or subjected to repeated burning.

e/ For unmanaged woodland with litter cover of less than 40%, C values should be taken from table 2.

TABLE 4: "P" Factors for Contouring, Contour Stripcropping and Terracing

Land Slope	P Values			
%	Contouring	Contour Stripcropping	Terracing a/	Terracing b/
2.0 to 7	0.50	0.25	0.50	0.10
8.0 to 12	0.60	0.30	0.60	0.12
13.0 to 18	0.80	0.40	0.80	0.16
19.0 to 24	0.90	0.45	0.90	0.18

a/ For erosion-control planning on farmland.

b/ For prediction of contribution to off-field sediment load.

(This Table appeared in SCS, 1972 p. 9).

TABLE 5: Guide for Assigning Soil Loss Tolerance Values (T) to Soils Having Different Rooting Depths

Rooting Depth	Soil Loss Tolerance Values Annual Soil Loss - Tons/ha (Tons/acre)	
cm (inches)	Renewable Soil a/	Non-Renewable Soil b/
0 - 25 (0-10)	2.2 (1)	2.2 (1)
25 - 50 (10-20)	4.5 (2)	2.2 (1)
50 - 100 (20-40)	6.7 (3)	4.5 (2)
100 - 150 (40-60)	9.0 (4)	6.7 (3)
150 (60)	11.2 (5)	11.2 (5)

a/ Soils with favourable substrata that can be renewed by tillage, fertiliser, organic matter, and other management practices.

b/ Soils with unfavourable substrata such as rock or soft rock that can not be renewed by economical means.

(This Table appeared in SCS, 1973 p. 4).

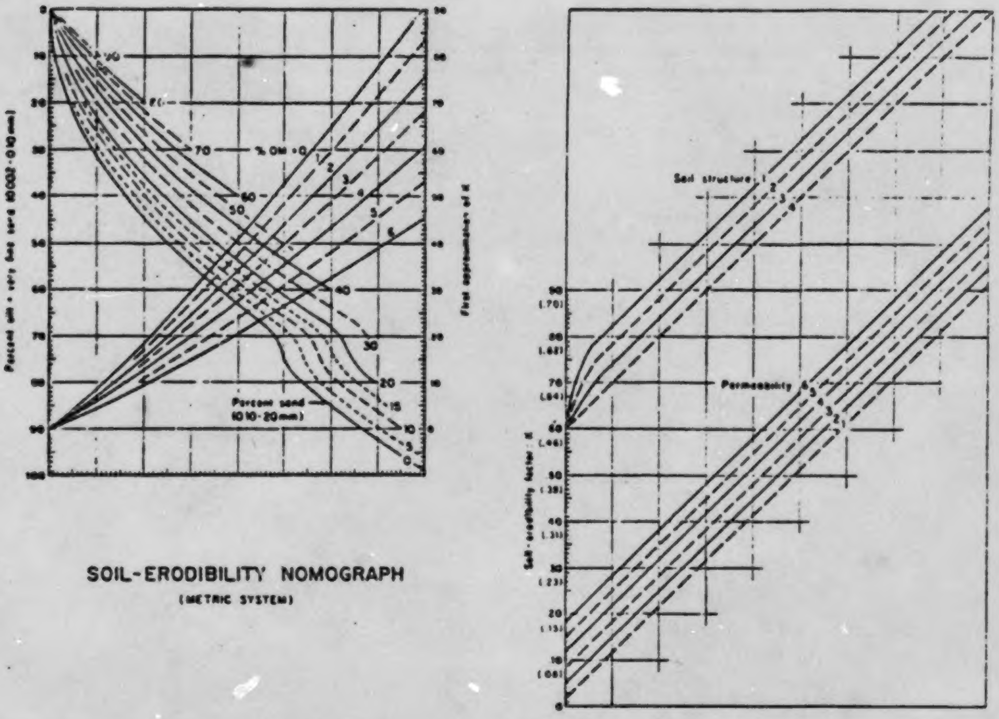

Figure 1. Soil erodibility nomograph. For codification and procedure see text. First approximation of K in SI-units only; final result of soil erodibility factor, K both in SI-units and pfs-units, with the latter in brackets. (Adapted from Wischmeier et al, 1971 Figure 1, p. 190).

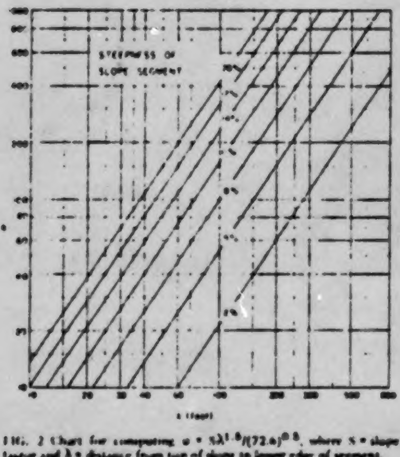

FIG. 2 Chart for computing $\omega = S\lambda^{1.5}/(72.6)^{0.5}$, where S = slope factor and λ = distance from top of slope to lower edge of segment.
(From: Foster and Wischmeier, 1974)

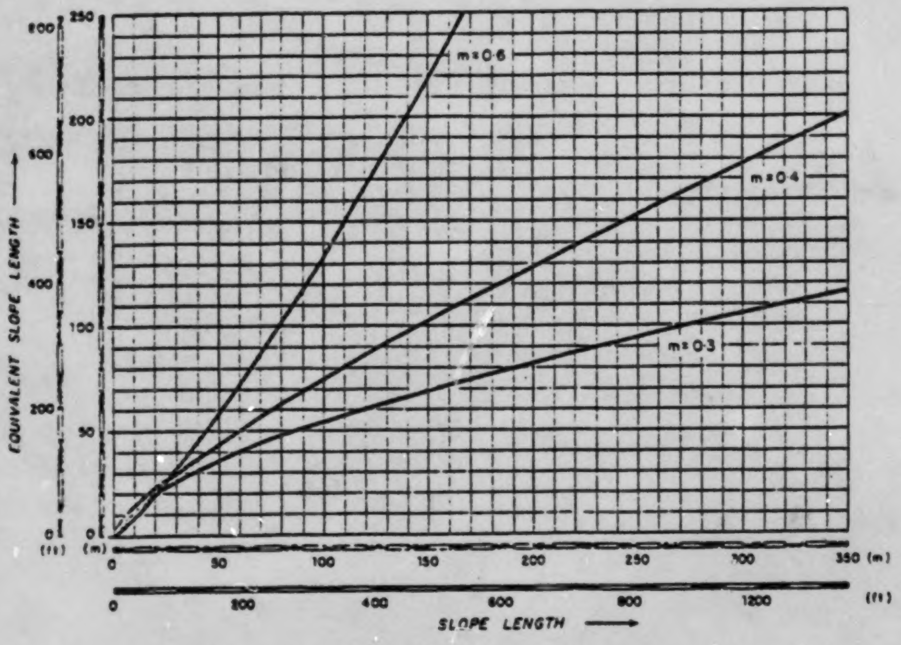

Figure 3 Equivalent slope lengths for use of slope-effect chart when the value of the pertinent slope length-exponent m is not 0.5. (Adapted from Wischmeier and Smith, 1965, Figure 3, p. 9). Note in the text also that λ = slope length (i.e., actual length on the ground).

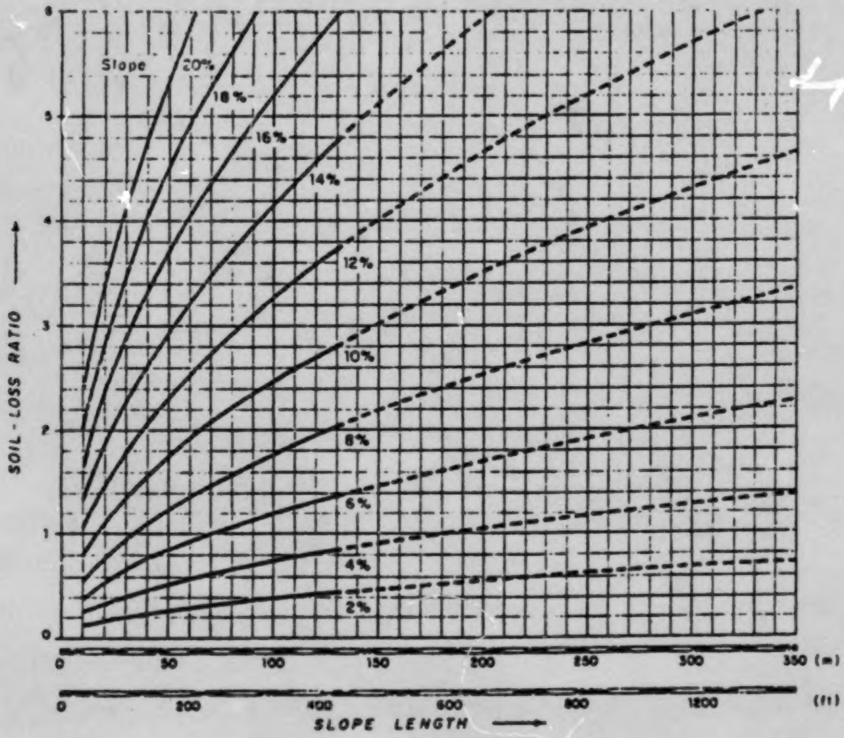

Figure 4 Slope-effect chart showing the combined effect of slope length λ and slope gradient S. (Adapted from Wischmeier and Smith, 1965 Figure 2, p. 8).

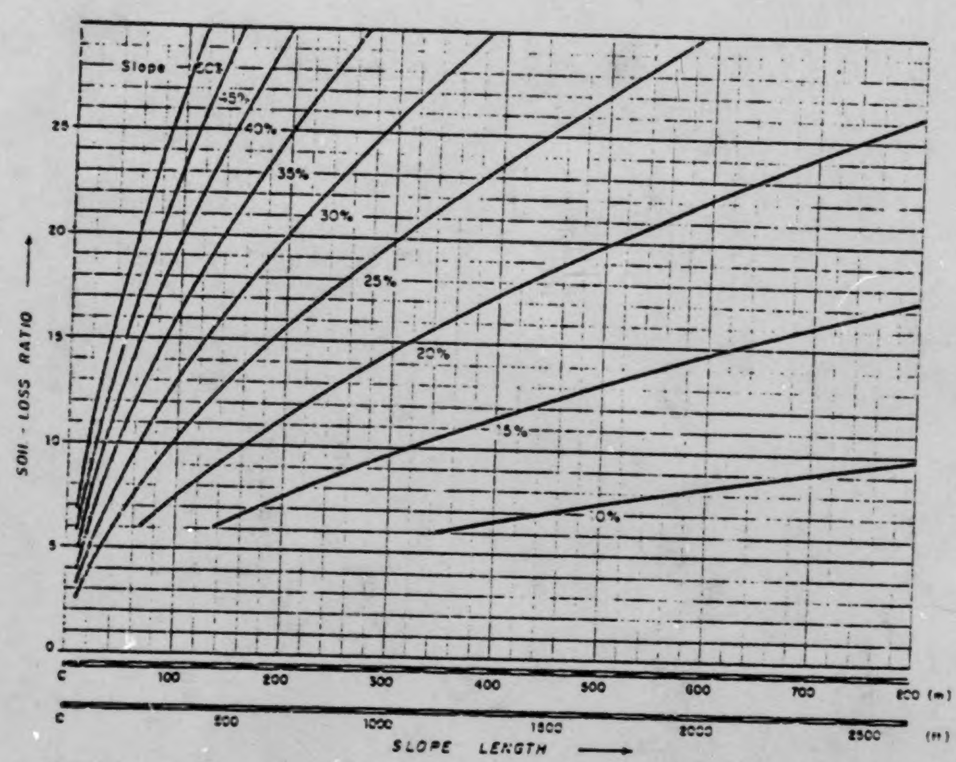

Figure [illegible] Slope-effect chart for slope lengths λ and slope gradients S exceeding those in Figure 6. Extrapolated beyond the range of the data; use only as speculative estimates. (Adapted from SCS, 1972 Figure 3, p. 6).

Landslides or Soil Mass Movement

adapted from: Swanston, D.H., Swanson, F.J., and Rosgen, D., in press, Soil Mass Movement, Chapter V., in AN APPROACH TO WATER RESOURCES EVALUATION, NON-POINT SOURCES SILVICULTURE (a procedural handbook). USDA Forest Service.

Principal Soil Mass Movement Processes

Downslope soil mass movements result primarily from gravitational stress. It may take the form of (1) failure, both along planar and concave surfaces, of finite masses of soil and forest debris which move rapidly (debris avalanches-debris flows) or slowly (slump-earthflows) (fig. 1); (2) pure rheological flow with minor mechanical shifting of mantle materials (creep) (fig 2); and (3) rapid movement of water-charged organic and inorganic matter down stream channels (debris torrents) (fig.3).

Slope gradient, soil depth, soil water content, and physical soil properties, such as cohesion and coefficient of friction, control the mechanics and rates of soil mass movement. Geological, hydrological, and vegetative factors determine occurrence and relative importance of such processes in a particular area.

Slump-Earthflows

Where creep displacement has exceeded the shear strength of soil, discrete failure occurs and slump-earthflow features are formed (Varnes 1958). Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow (Varnes 1958). Geologic vegetative, and hydrologic factors have primary control over slump-earthflow failure, particularly where these materials are overlain by hard, competent rock (Wilson 1970, Swanson and James 1975). Earthflow movement also appears to be sensitive to long-term fluctuations in soil water content (Wilson 1970, Swanston 1976).

Because earthflows are slowly moving, deep-seated, poorly drained features, individual storms probably have much less influence on their movement than on the likelihood of occurrence of debris avalanches-debris flows. Where planes of slump-earthflow are more than several meters deep, wieght of vegetation and vertical root anchoring effects are insignificant.

Earthflows can move imperceptibly slowly to more than 1 m/day in extreme cases. In parts of northwestern North America, many slump-earthflow areas appear to be inactive (Colman, 1973; Swanson and James, 1975). Where they are active, rates of movement have been monitored directly by repeated surveying of marked points and inclinometers and by measuring deflection of roadways and other inadvertent reference systems. These methods have been used to estimate the rates of earthflow movement shown in table 1 (Swanston and Swanson 1976, Kelsey 1977).

The area of occurrence of slump-earthfolows is mainly determined by bedrock geology. For example,in the Redwood Creek basin, northern California, Colman (1973) observed that of the 27.4 percent of the drainage which is in slumps, earthflows, and older or questionable soil mass movements, as very high percentage of the unstable areas are located in clay-rock and pervasively sheared sedimentary rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated soil mass movement. The area of occurrence of slump-earthflows in volcanic terrains has also been closely linked to bedrock (Swanston and Swanson 1976). There are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction in the western United States (Wilson 1970). Undercutting the toes of earthflows and piling rock and soil debris on slump blocks are common practices which influence slump-earthflow movement. Stability of such areas is also affcted by modification of drainage systems, particularly where road drainage systems route additional water into the slump-earthflow areas. These disturbances may increase movement rates from a few millimeters per year to many centimeters. Once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Although the impact of deforestation alone on slump-earthflow movement has not been demonstrated quantitativey, evidence suggests that it may be significant. In massive, deep-seated failures, lateral and vertical anchoring by tree root systems is negligible. Hydrologic impacts of deforestation, however, appear to be important. Reduced evapotranspiration will increase soil moisture availability. This water is, therefore, free to pass through the rooting zone to deeper levels of the earthflow.

Debris Avalanches-Debris Flows

Debris avalanches-debris flows are rapid, shallow soil mass movements from hillslope areas. Here the term "debris avalanche-debris flow" is used in a general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) and others on the basis of increasing water content and type of included material. From a land management standpoint, there is little purpose to differentiating amoung the types of shallow hillslope failures, since the mechanics and the controlling and contributing factors are the same. Areas prone to debris avalanches-debris flows are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces. Because debris avalanches-debris flows are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle are potentially important influence. Factors which influence antecedent soil moisture conditions and the rate of water supply to the soil during snowmelt and rainfall also have significant control over the time and place of debris avalanches-debris flows.

The rate of occurrence of debris avalanches-debris flows is controlled by the stability of the landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanches debris flows will vary from one geomoephic-climatic setting to another. Table 2 (Swanston and Swanson 1976) shows that annual rates of debris avalanche erosion from forested study site in Oregon and Washington in the United States, and British Columbia in Canada, range from 11 to 72m3/km2/yr. These estimates are based on surveys and measurements of debris avalanche erosion during a particular time period (15 to over 32 years) over a large area (12 km2 or larger).

An analysis of harvesting impacts in the western United States (Swanston and Swanson 1976)(table 2) reveals that timber harvesting commonly results in an acceleration of soil mass movement activity by a fctor of 2 to 4 times relative to forested areas. In the four study areas listed in table 2, road-related debris avalanche erosion was increased by factors ranging from 25 to 340 times the rate of debris avalanche erosion forested areas. The great variability in the impact of roads reflects not only differences in the mature stability of the landscape, but also, and more importantly from an engineering standpoint, differences in site location, design, and construction of roads.

Soil Creep

Soil creep is defined as the slow, downslope movement of soil mantle materials as the result of long-term applicationof gravitational stress. The mechanics of soil creep have been investigated experimentally and theoretically (Terzaghi 1953, Goldstein and Ter-Stepanian 1957, Saito and Uezawa 1961, Culling 1963, Haefeli 1965, Bjerrum 1967, Carson and Kirkby 1972). Movement is quasi-viscous; it occurs under shear stresses sufficient to produce permanent deformation, but too small to result in discrete failure. Mobilization of the soil mass is primarily by deformation at grain boundaries and within clay mineral structures. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains thereby reducing friction within the soil mass. Creeping terrain can be reccognized by characteristic rolling, hummocky topography with frequent sag ponds, springs, and occasional benching due to local rotational slumping. Local discrete failures, such as debris avalanches and slump-earthflows, may be present within the creeping mass (fig. 5).

Natural creep rates monitored in different geological materials in the western Cascade and Coast Ranges of Oregon and northern California indicate rates of movement between 7.1 and 15.2 mm/yr, with the average about 10 mm/yr (Swanston and Swanson 1976) (table 3). The most rapid movement usually occurs at or near the surface, although the significant displacment may extend to variable depths associated with incipient fialure planes or zones of ground water movement. Active creep depth varies greatly and largely depends on parent material origin, degree and depth of weathering, subsurface structure, and soil water content. Most movement appears to take place during rainy season maximum soil water levels (figs. 4a), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (fig. 4b). This is consistent with Ter-Stepanian's (1963) theoretical analysis which shows that the downslope creep rate of an inclined soil layer is exponentially related to piezometric level in the slope.

There have been no direct measurements of the impact of deforestation on creep rates in the forest environment, mainly because of the long periods of records needed both before and after a disturbance. There are, however, a number of indications that creep rates are accelerated by harvesting and road construction.

In the United States, Wilson, (1970) and others have used inclinometers to monitor accelerated creep following modifcation of slope angle, compaction of fill materials, and distribution of soil mass at construction sites. The common occurrence of shallow soil mass movements in these disturbed areas and open tension cracks in fills along roadways suggests that similar features along forest roads indicate significantly accelerated creep movement.

On open slopes where deforestation is the principal influence, impact on creep rates may be more subtle, involving modifications of hydrology and root strength. Where creep is a shallow phenomenon (less than several meters), the loss of root strength caused by deforestation is likely to be significant. Reduced evapotranspiration after clearcutting (Gray 1970, Rothacher 1971) may result in longer duration of the annual period of creep activity and, thereby, increase the annual creep rate.

Brown and Sheu (1975) have developed a mathematical model of creep which accounts for root strength, wind stress on the soil mantle weight of vegetation,and soil moisture. The model predicts a brief period of slope stability after clearcutting due to removal of the weight of vegetation and elimination of wind stress. Thereafter, creep rates are accelerted as soil strength is attenuated by progressive evapotranspiration. The net result of the short-term increase and longer term decrease in slope stablity is expected to be an overall increase in creep activity.

Debris Torrents

Debris torrents involve the rapid movement of water-charged soil, rock, and organic material down steep stream channels. They typically occure in steep, intermittent,and first- and second-order channels. They are triggered during extreme discharge by debris avalanches from adjacent hillslopes which enter a channel and move directly downstream or by the breakup and mobilization of debris accumulations in the channel. The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and organic material from the streambed and banks. Some torrents retriggered by debris avalanaches of less than 10 yd3 (76 m3), but ultimately involve 1,000 yd3 (760 m3) of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of meters of channel may be scoured to bedrock. When a torrent n loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material coverig areas of up to several hectares.

The main factors controlling the occurrence of debris torrents are the quantity and stability of adjacent hillslopes,and peak discharge characteristics of the channel. The concentration and stability of debris in channels reflect the history of stream flushing and the health and stage of development of the surrounding timber stand (Froehlick 1973). The stability of adjacent slopes depends on factors described in previous sections. The history of storm flows has a controlling influence over the stability of both soils on hillslopes and debris in stream channels. Velocities of debris torrents, estimated to be up to several tens of meters/second, are known only from a few verbal and written accounts.

Deforestation appears to dramatically accelerate the occurrence of debris torrents by increasing the freqency of debris avalanches. Although it has not been demonstrated, it is also possible that increased concentrations of unstable debris in channels during forest harvesting (Rothacher 1959, Froehlich 1973, Swanson and others 1976) and possible increased peak dischages (Rothacher 1973, Harr and others 1975) may accelerate the frequency of debris torrents.

The impact of clearcutting and road construction on frequency of deris torrents (events/km2/yr) may be compared to debris torrent occurrence under natural conditions. In the H. J. Andrews Experimental forest and Mhe Alder Creek study sites in Oregon,Mtimber havesting appeared to increase occurrence)f debris torrents by 4.5 and 8.8 times; and roads were responsible for increases of 42.5 and 13) tMmes relative to forested areas.

Although the quantitative reliability of these estimates of harvesting impacts is limited by the small number of events analyzed, there is clear evidence of mared acceleration in the frequency of debris avalanches–debris flows as a result of forest harvesing and road building. The histories of debris avalanches–debris flows as a result of forest harvesing and road building. The histories of debris avalanches–debris flows in the two study areas clearly indicate that increased deris torrent occurrence is primarily a result of two conditions: debris avalanches trigger most debris torrents (table 4) and the occurrence of deris avalanches–debris flows is temporarily accelerated by deforestation and road construction (table 2).

Mechanics of Movement

Direct application of soil mechanics theory to analysis of soil mass movement porcesses is difficult because of the heterogeneous nature of soil materials, the extreme variability of soil water conditions, and the related variations in stress–strain relationships with time. However, the theory provides a convenient framework for disussing the mineral mechanism and the complex interrelationships of the various factors active in development of soil mass movements on mountain slopes.

In terms of factor of safety analysis, the stability of soils on a slope can be expressed as a ration between shear strength, or resistance of the soil to sliding, and the downslope pull of gravity or gravitational stress. As long as shear strength exceeds the pull of gravity, the soil will remains in a stable state (Terzaghi 1950, Zaruba and Mencl 1969).

It is important to remember that soil mass movements result from changes in the soil shear strength–gravitational stress relationship in the vicinity of failure. This may involve a mechanical readjustment among individual particles or a more complex interaction between both internal and external factors acting on the slope.

Figure 5 shows the geometrical relationship of factors acting on a small portion of the soil mass. Any increases in gravitational stress will increase the tendency for the soil to move downslope. Increases in gravitational stress result from increasing inclination of the sliding surface or increasing unit weight of the soil mass. Stress can also be augmented by: (1) the presence of zones of weaknesses in the soil or underlying bedrock produced by bedding planes and fractures, (2) application of wind stresses transferred to the soil through the stems and root systems of trees, (3) strain or deformation in the soil produced by progressive creep, (4) fractional "drag" produced by seepage pressure, (5) horizontal accelerations due to earthquakes and blasting, and (6) removal of downslope support by undercutting.

Shear strength is governed by a more complex interrelationship between the soil and slope charcteristics. Two principal forces are active in resisting downslope movement. These are: (1) cohesion or the capacity of the soil particles to adhere together, a soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and (2) the frictional resistance between individual particles and between the soil mass and the sliding surface. Frictional resistance is controlled by the angle of internal friction of the soil – the degree of interlocking of individual grains – and the effective weight of the soil which includes both the weight of the soil mass and any surface loading plus the effect of slope gradient and excess soil water.

Pore water pressure — pressure produced by the head of water in saturated soil and transferred to the base of the soil through the pore water – acts to reduce the frictional resistance of the soil by reducing its effctive weight. In effect, its action causes the soil to "float" above the sliding surface.

Controlling and Contributing Factors

Particle size distribution or "texture" (which governs cohesion), angle of internal friction, soil moisture content, and angle of sliding surface are the controlling factors in determining stability of a steepland soil. For example. shallow coarse-grained soils low in clay-size particles have little or no cohesion, and frictional resistance determines the strength of the soil mass. Frictional resistance is, in turn, strongly dependent on the angle of internal friction of the soil and pore water pressure. A low angle of internal friction relative to slope angle or high pore water pressure can reduce soil shear strength to negligible values.

Slope angle is a major indicator of the stability of low cohesion soils. Slopes at or above the angle of internal friction of the soil indicate a highly unstable natural state.

Soils of moderate to high clay content exhibit more complex behavior because resistance to sliding is determrined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture. In a dry state, clayey soils have a high shear strength with the internal angle of friction quite high (>30°). Increasing water content mobilizes the clay through absorption of water onto the clay structure. The angle of internal friction is reduced by the addition of water to the clay lattices (in effect reducing "intragranular" friction) and may approach zero in saturated conditions. In addition, water between grains – interstitial water – may open the structure of the soil mass. This permits a "remolding" of clay friction,transforming it into a slurry, which then lubricates the remaining soil mass. Some clays are more susceptible to defrmation than others, making clay mineralogy an important conideration in areas charcterized by quasi-viscous flow deformation of "creep." Swelling clays of the smectite group (montmorillenite) are particularly unstable because of their tendency to absorb large quantities of water and to experience alternate expansion and contraction during periods of wetting and drying which may result in progressive failure of a slope. Thus, clay-rich soils have a high potential for failure given excess soil moisture content. Under these conditions, failures are not directly dependent on sliding surface gradient as in cohesionless soils, but may develop on slopes with gradients as low as 2° or 3°.

Parent material type has a major effct on the particle size distribution, depth of weathering, and relative cohesiveness of a steepland soil. It frequently can be used as an indicator of relative stability or potential stability problams. In humid regions where chemical weathering predominates, transformation of easily weathered primary minerals to clays and clay-size particles may be extensive. Siltstones, clay stones, shales, nonsiliceous sandstones, pyroclastics, and serpentine-rick rocks are the most easily altered and are prime candidates for sol mass movement of the creep and slump-earthflow types. Conversely, in arid or semiarid regions, slopes underlain by these rocks may remain stale for many years due to slow chemical weathering processes and lack of enough soil moisture to mobilize existing clay minerals. On steep lands underlain by resistant rocks, especially where mechanical weathering prevails, soils are usually coarse and lose in clay-size particles. Such areas are more likely to develop soil mass movements of the debris avalanche-debris flow type.

Parent material structure is a critical factor in stablity of many shallow soils. Highly jointed bedrock slopes with principal joint planes parallel to the slope provide little mechanical support to the slope and create avenues for concentrated subsurface flow and active pre water pressure development, as well as ready-made zones of weakness and potental failure surfaces for the overrlying material. Sedimentary rocks with bedding planes parallel to the slope, function in essentially the same way, with the uppermost bedding plane forming an impermeable boundary to subsurface water movement, a layer restricting the penetration and development of tree roots, and a potential failure surface. Vegetation cover generally helps control the amount of water reaching the soil and the amount held as stored water against gravity, largely through a combination of interception and evapotranspiration. The direct effect of interception on the soil water budget is probably not large, especially in areas of high total rainfall or during large storms, where interception is effective, probably have little influence on total soil water available for activating mass movements.

In areas of low rainfall, the effect of evapotranspiration is much more pronounced, but it is particularly dependent on region and rainfall. In areas charcterized by warm, dry summers, evapotranspiration significantly reduces the degree of saturation resulting from the first storms of the fall recharge period. This effect diminishes as soil water deficit is satisfied. Once the soil is recharged, the effects of previous evapotranspirational losses become negligible. Conversely, in areas of continuous high rainfall or those with an arid or semiarid climate, evapotranspirational effects are probably negligible. Depth of evapotranspirational withdrawals is important also. Deep withdrawals may require substantial recharge to satisfy the soil water deficit, delaying or reducing the possibility of saturated soil conditions necessary for major slideproducing events. Shallow sosls, however, recharge rapidly, possibly becoming saturated and most unstable during the first major storm.

Root systems of trees and other vegetation may increase shear strength in unstable soils by anchoring through the soil mass into fractures in bedrock, providing continuous long fiberous binders within the soil mass, an tying the slope together across zones of weakness or instability.

In shallow soils, all three effects may be important. In deep soils, the anchoring effect of roots becomes negligeable but the other parameters will remain important. In one extremely steep area in western North America, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area (Swanston and Swanson 1976).

Snow cover increases soil unit weight by surface loading and affects delivery of water to the soil by retaining rainfall and delaying release of much water. Delayed release of melt water, coupled with usually heavy storms during a midwinter or early spring warming trend, has been identified as the principal initiating factor in recent major landslide activity on forest lands in central Washingron (Klock and Helvey 1976).

Characterizing Unstable Slopes in Forested Watersheds

The following guidelines are designed to help delineate the hazards of unstable slopes on forested lands.

There are six environmental qualities that should be carefully considered when judging stability of natural slopes in terms of surface erosion and soil mass movement. They are:

A. landform features
B. soil characteristics
C. bedrock lithology and structure
D. vegetative cover
E. hydrologic characteristics of site
F. climate

Each of these qualities encompasses a group of factors which control stability conditions on the slope and determine or identify the type of processes and movements which are most likely to occur.

Key factors identifying potentially unstable slopes on any mountainous terrain include slope gradient (a landform quality) and concentration of precipitation (both intensity and duration). Soil properties, including soil depth and such diagnostic characteristics as texture, permeability, angle of internal friction, and cohesion determine the types of processes that will dominate and, to some degree, determine the stable slope gradient within a particular soil type. Bedrock structure, especially attitude of beds and degree of fracturing or jointing, are important contributing factors controlling local stability conditions. Many of these factors are identifiable on the ground or in readily available support documentation (climatological records, etc.).

The following outline discusses the six environmental qualities important for judging stability of natural slopes and the key factors associated with each.

A. Landform features

1. Landforms on which subject area occurs. A qualitative indicator of potentially unstable landform types. Obtainable from air photos and topographic maps. For example, alpine glaciated terrain characteristically exhibits U-shaped valleys with extensive areas of very steep slopes. Fracturing parallel to the slope is common, and soils, either of colluvial or glacial origin, are usually shallow and cohesionless. The underlying impermeable surface may be either bedrock or compact glacial till. Such terrain is frequently subject to debris avalanche-debris flow processes.

Areas formed by continental glaciation commonly exhibit rolling terrain consisting of low hills and ridges composed of bedrock, glacial till, and stratified drift separated by areas of ground moraine and glacial outwash. Glaciolacustrine deposits may be present locally, consisting of thick deposits of silt and clay which may be particularly subject to slump-earthflow processes if disturbed.

Fluvially formed landscapes underlain by bedded sedimentary and meta-sedimentary rocks may have slope steepness controlled by jointing, fracturing, and faulting; by orientation of bedding; and by differential resistance of alterating rock layers. Debris avalanche-debris flow failures frequently occur in shallows colluvial soils along these structurally controlled surfaces. Slump-earthflow failures may occur in clay-rock or deeply weathered units, in deeply weathered soils and colluvial debris on the lower slopes, and in valley fills adjacent to active stream channels.

Volcanic terrain consisting of units of easily weathered volcaniclastic rocks and hard, resistant flow rock commonly exhibit slump-earthflow failures in deeply weathered volcanisclastic materials. Such failures usually occur just below a capping flow or just above an underlying flow due to concentration of ground water. Debris avalanche-debris flow failures are common in shallow residual or colluvial soils developed on the resistant flow rock units.

Because of the large variability in landform processes and the modifying influence of climatic conditions on weathering rates and products, geologists with some knowledge of the area should be consulted.

2. **Slope configuration.** - Shape of the slope in the area of consideration. A qualitative indicator of location and extent of most highly unstable areas on a slope. Obtainable from air photos and topographic maps. On both concave and convex slopes, usually the steepest portions have the greatest stability hazard. Convex slopes may have oversteep gradients in lower portions of the slope. Concave slopes have oversteep gradients in their upper elevations.

3. **Slope gradient.** - A key factor controlling soil stablity in steep mountain watersheds. Slope gradient may be quantified on the ground or from topographic maps. It determines effectiveness of gravity acting to move a soil mass downslope. For debris avalnche-debris flow failures, this is a major indicator of the natural soil mass movement hazard. For slump-earthflow failures, this is not as important since, given the right conditions of soil moisture content, soil texture, and clay mineral content, failures can occur on slope gadients as low as 2° or 3°. Slope gradient also has a major effect on subsurface water flow in terms of drainage rate and susequent susceptibility to temporary water table buildup during high intensity storms.

B. Soil Characteristics

1. Present soil mass movement type and rate. Obtainable from air photos and field checks. This is a qualitative indicator of size and location of potential stability problems, type of recent landsliding, and kinds of soil mass movement processes operative on the slope. These, in turn, suggest probable soil depth and certain dominant soil characteristics. For example, debris avalanches-debris flows most frequently develop in shallow, coarse-grained soils which have a low clay content or in deeply weathered pelitic sediments, serpentinite, and volcanic ash and breccia.

2. Parent material. - A qualitative indicator of probable shape of soil particles, bulk density (or weight), degree of cohesion or clay mineral content, soil depth, permeability, and presence or absence of impermeable layers in the soil. These, in turn, suggest types of soil mass movement processes operative within an area. This information is obtainable from existing geologic and soil survey maps, by air photo inerpretation, and by field check.

Soils developed from colluvial or residual materials and some tills and pumice soils commonly possess little or no cohesion. Failures in such soils are usually of the deris avalanche-debris flow type.

Soils developed from weathered fine grained sedimentary rocks (mudstones, claystones, nonsiliceous sandstone chales), volcaniclastics, and glacio-lacustrine clays and silts possess a high degree of cohesion and characteristically develop failures of the slump-earthflow type.

The mica content also has a major influence on soil strength. Ten to twenty percent mica will produce results similar to high clay content.

3. Occurrence of compacted, cemented, or impermeable layer. - A qualitative indicator of the depth of potentially unstable soil and probable principal planes of failure on the slope. This information is obtanable from borings, soil pits, and inspection of slope failure scars in the field.

4. Evidence of concentrated subsurface drainage (including evidence of seasonal saturation). - A qualitative indicator of local zones of periodic high soil moisture content including saturation and potentially active pore water pressure during high rainfall periods. These identify potential areas of slope failure. This information is obtainable by air photo interpretation and ground observation. Diagnostic features include broad linear depressions perpendicular to slope contour, representing old landslide site and areas on the slope, representing springs and areas of concentrated ground water movement.

5. **Diagnostic soil characteristics.** - Key factors in determining dominant types of soil mass movement process mechanics of motion and probable maximum and minimum stable slope gradients for a particular soil. This is identifiable through field testing, sampling, and laboratory analysis. Data on benchmark soils also may be obtained from soil surveys and engineering analyses for road construction in or adjacent to the proposed silvicultural activity.

a. **Soil depth.** - Principal component of the weight of the soil mass and an important factor in determining soil strength and gravitational stress acting on an unstable soil.

b. **Texture** - (Particle size distribution) the relative proportions of sand (2.0 - 0.5 mm), silt (0.5 - .002 mm), and clay (<.002 mm) in a soil. Texture, along with clay mineral content, are important factors in controlling cohesion, angle of internal friction, and hydraulic conductivity of an unstable soil.

c. **Clay mineralogy.** - An indicator of sensitivity to deformation. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas where creep occurs. "Swelling" clays of the smectite group (montmorillonite) are particularly unstable.

d. **Angle of internal friction** - An indicator of the internal frictional resistance of a soil caused by intergranular friction and interlocking of individual grains, an important factor in determining soil shear strength or resistance to gravitational stress. The tangent of the angle of inernal friction times the weight of the soil constitute a mathematical expression of frictional resistance. For shallow, cohesionless soils, a slope gradient at or above the angle of internal friction times the weight of the soil constitute a mathematical expression of frictional resistance. For shallow, cohesionless soils, a slope gradient at or above the angle of internal friction is a good indicator of a highly unstable site.

e. **Cohesion.** - The capacity of soil particles to stick or adhere together. This is a distinct soil property produced by cementation, capillary tension, and weak electrical bonding of organic colloids and clay particles. Cohesion is usually the direct result of high (20 percent or greater) clay particle content and is an important contributor to shear strength of a fine grained soil.

C. Bedrock Lithology and Structure

1. **Rock type.** - A qualitative indicator of overlying silt texture, clay mineral content, and relative cohesiveness. It provides a regional guide to probable areas of soil mass movement problems and dominant porcesses. For example, in the Cascades and Coast Range of Oregon and Washington, areas underlain by volcanic ash and breccias and silty sandstone are particularly susceptible to slump-earthflows. Where hard, resistant volcanic flow rock is present, shallow planar failures dominate. Slopes underlain by granites and diorites are also more susceptible to shallow planar failures although where extensive chemical weathering has occurred, such rocks may exhibit slump-earthflow features. The slope stability characteristics of a particular rock type of formation largely depend on mineralogy, climate, and degree of weathering, and must be determined for each particular area.

2. **Degree of weathering.** - A qualitative indicator of soil depth and type of siol mass movement activities. In some rock types, it is also an indicator of degree of clay mineral formation.

3. **Attitude of beds.** - Quantifiable on the ground, from geologic maps, and occasionally from air photos. This is an important contributing factor to unstable slopes, especially where attitude of bedding parallels or dips in the same direction as the slope. Under these conditions, the beddig planes form zones of weakness along which slope failures can occur due to high pore water

pressures and decreases in frictional resistance. Conversely, bedding planes dipping into the slope frequently produce natural buttresse and increase slope stability. Care must be taken in assessing the stabilizing influence of horizontal or in-depping bedding planes particularly where well-developed jointing is present (see no. 4).

4. Degree of jointing and fracturing - Quantifiable on the ground and occasionally from geologic maps as dip and strike of faults, fractures, and joint systems. Joints in particular are important contributing factors to slope instabilty, especially on slopes underlain by igneous materials. Joints parallel to or dipping in the same directions as the slope, create local zones of weakness along which failures occur. Jointing also provides avenues for deep penetratin of groundwater with subsequent active pore water pressure development along downslope dipping joint planes.

Valleys developed along high angle faults in mountainous terrain may have exceptionally steep slopes. Deep penetratin of ground water into uneroded fault and shear zones can result in extensive weathering and alteration of zone materials, resulting in generation of slump-earthflow failures. Such zones can also form barriers to ground water movement cauing redirection and concentration of water into adjacent potentially unstable sites.

D. Vegetative Characteristics

1. Root distribution and degree of root anchoring in the subsoil. - An indicator of effectiveness of tree roots as a stabilizing factor in shallow steep slope soils. Quantifiable on the ground by observing the degree of penetration of roots through the soil and into a more resistant substratum and by measuring the biomass of the roots contained in a potentially unstable soil. High biomass of contained roots is an expression of the binding capacity of "reinforcing" of roots to the soil mass.

2. Vegetation type and distribution. - Cover density, vegetation type, and stand age are qualitative indicators of the history of soil mass movement on a site and soil and ground water conditions. This information is obtainable by air photo interpretation and ground checking.

E. Hydrologic Characteristics

1. Hydraulic conductivity. - A measure of water movement in and through soil material. This is quantifiable in the field and in the laboratory using pumping tests and permeameters. Low hydraulic conuctivities mean rapid storm generated saturation and a high probability of active pore water pressure, which produces highly unstable conditions in steep slope soils.

2. Pore water pressure. - A measure of the pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water. This is quantifiable in the field through measurement of free water surface level in the soil. Pore water pressure is a key factor in failure of a steep slope soil, and operates primarily by reducing the weight component of soil shear strength.

F. Climate

1. Precipitation occurrence and distribution. - A key factor in predicting regional soil mass movement occurrences. Most soil mass movements are triggered by soil saturation and actve pore water pressures produced by rainfall of high intensity and long duration. Isohyetal maps of rainfall occurrences and distribution, constructed from data obtainable from local monitoring stations or from the Weather Bureau, can be used to pinpoint local areas of high rainfall concentration. It is advisable to develop a simple relationship between rainfall intensity and pure water pressure development for a particular soil type or area of interest so that magnitude and return period of damaging storms can be identified. This can be done simply by locating a rain gage at the site or using near by rainfall data and correlating this with piezomtric data obtained from open-ended tubes installed to the probable depth of failure at the site. Each storm should be monitored.

Estimating Soil Mass Movement Hazard and Sediment Delivered to Channels

This section delineates a procedure to be used on potentially unstable areas to analyze the hazard of soil mass movement associated with silvicultural activities and to determine the potential volume and delivery of inorganic material to the closest drainageway. This is a broad level analysis designed to determine where specific controls or management treatment variations are required because of possible water quality changes resulting from soil mass movement. This procedure will not substitute for site specific analysis of road design, maintenance, and rehabilitation as may be required under current management procedures.

To assess soil mass movement hazards that might deliver inorganic material to a stream course, a basic qualitative evaluation is undertaken based on the following information:

1. A delineation of hazard areas and dominant soil mass movement types using aerial photo and topographic map interpretation with minimum ground reconnaissance.

2. An estimate of the likelihood of failure or "sensitivity" of an area caused by both natural and man-induced events, using subjective analysis of controlling and ocntributing factors within defined hazard areas.

3. An estimate of the volume of material released by soil mass movements during storm events with a 10-year return inerval or less.

4. An estimate of the volume of sediment released by soil mass movements which actually reach a water course based on slope position, gradient, and shape and type of movement.

Although soil mass movements are too infrequent for effective direct annual evaluation, delivery volumes can be expressed on an average annual basis for purposes of comparison between pre- and post-silvicultural activity conditions.

A broad delineation of potentially unstable terrain by slope characteristics and soil mass movement types is an essential part of the hazard analysis. A detailed flow chart (fig. 6) shows the sequence of analysis once the delineation of unstable terrain is accomplished.

The limits placed on variable ranges for high, medium and low hazard indices are approximating professionals. The weighted values for hazard indices reguides only, and they were determined from consultation with practicing professionals as well as a limited analysis of several unstable areas in Colorado and western Oregon. However, they do reflect the relatve importance of the idividual factors and their effects on likelihood of failure by the major soil mass movement types. These weightings and the ranges of hazard index should be adjusted to reflect the conditions prevalent within a given area.

Procedural Description

The following information decribes each step of the procedural flow chart, fig. 6. Data from the Horse Creek example are used to illustrate the following procedure. This complete example is presented in "Chapter VIII: Procedural Example."

Broad Delineation of Potentially Unstable Areas

Guidelines have been presented that provide a qualitative characterization of unstable or potentially unstable slopes on forested lands. Using these guidelines, evaluate the area of the proposed silvicultural activity to ascertain the stability of the site.

Identify and Map Areas by Soil Mass Movement Type

If the area is generally unstable or potentially unstable, delineate the hazard areas and dominant soil mass movement types (debris avalanches-debris flows and slump-earthflows) using aerial photos and topographic map interpretation. Potentially unstble areas are those that may become unstable due to the proposed silvicultural activity. Unstable areas are those that have or presently are undergoing a soil mass movement.

Characterize Soil Mass Movement Type

Soil mass movements have been classified into two major types; debris valanches-debris flows and slump-earthflows. Several site parameters and management activities can be used to evaluate the possibility of soil mass movement. Although both movement types hve similar facts that can be used to evaluate the hazard of a failure, the relative importance of these factors may be different between the two movement types. In addition, each kind of soil mass movement has some site or management activity parameters that are specific for that movement. Therefore, to evauate the hazard of a soil mass movement, each type must be evaluated separately using the factors that have been found to be significant in characterizing that particular kind of failure.

Debris Avalanche-debris Flow

Areas prone to debris avalanches-debris flows are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces.

Natural Hazard Site Characteristics

For debris avalanches-deris flows, the following site characteristics have been found to be criticl in evaluating the potential hazard of a natural soil mass movement slope gradient, soil depth, subsurface drainage characteristics, soil texture, bedding structure and orientation, surface slope configuration, and precipitation input. This information can be obtained from geologic and soils maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site charcteritic is indicated in table 5 and worksheet 1 by the weighting value assigned.

Management Induced Hazard Characteristics

For debris avalanches-debris flows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement; vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table 6 and worksheet 2 by the weighting value assigned.

Hazard Index

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numerical ratings are subjective and depend on who is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for debris avalanches-debris flows is determined by summing the weighted values from worksheet 1 and comparing this value to the ranges of values fr high, medium, and low hazard indices. For example, if the sum of the weighted values for the natural hazard index (worksheet 1) was 31, the hazard index would be medium. The value 31 falls within the range of values (22-44) for the medium hazard.

The relative hazard for debris avalanches-debris flows caused by silvicultural activities is determined by summing the weighted values from worksheet 2. The overall hazard index caused by natural plus existing proposed silvicultural acitvities is determined by adding the total weighted value for he natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 31, the overall wieghted value of both the natural (31) plus the silvicultural activity (31) would be equal to 62 and the overall hazard index would be high.

Slump-Earthflow

Slump-earthflow prone areas are typified by deep. cohesive soils and clay-rock bedrock overlying hard, competent rock. Slump-earthflow soil mass movement also appears to be sensitive to long-term fluctuations.

Natural Hazard Site Characteristics

For slump-earthflows, the following site characteristics have been found to be critical in evaluating the potential hazard of a natural soil mass movement: slope gradient, sub-surface drainage characteristics, soil texture, surface slope configuration, vegetative indicators, bedding structure and orientation, and precipitation input. This information can be obtained from soils maps, vegetative cover maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site characteristic is indicated in table 7 and worksheet 3 by the weighting value assigned.

Management Induced Hazard Characteristics

For slump-earthflows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement: vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities or from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table 8 and worksheet 4 by the weighting value assigned.

Hazard Index

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numberical ratings are subjective and depend on what is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for slump-earthflows is determined by summing the weighted values from worksheet 3 and comparing this value to the ranges of values for high, medium, and low hazard index. For example, if the sum of the wighted values for the natural hazard index (wksht. 3) was 38, the hazard index would be medium. The value 38 falls within the range of values (22-44) for the medium hazard.

The relative hazard for slump-earthflows caused by silvicultural activities is determined by summing the weighted values form worksheet 4. The overall hazard index resulting from natural plus existing or proposed silvicultural activities is determined by adding the total weighted value from silvicultral activites to the total weighted value for the natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 8, the overall weighted value of both the natural (38) plus the silvicultural activity (8) would be equal to 46, and the overall hazard index would be high.

Bibliography not available at time of printing.

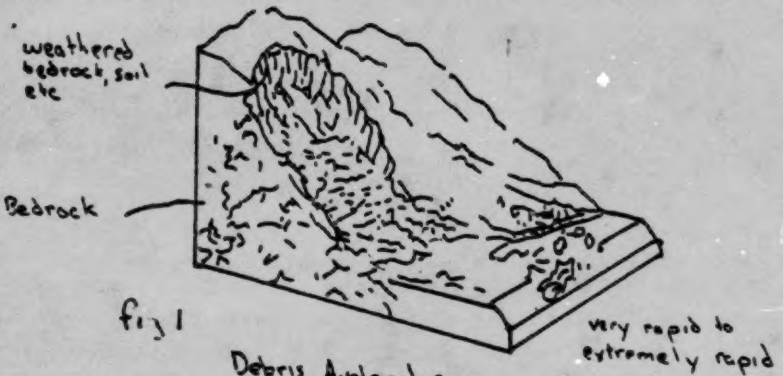

fig 1 Debris Avalanche

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fig. 2

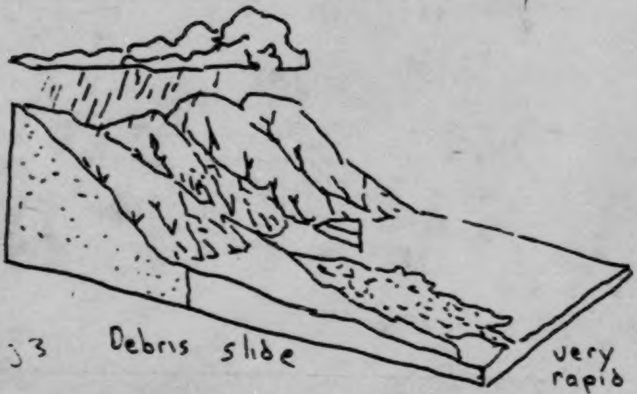


fig 3 Debris slide

Table 1. Observations of movement rates of active earthflows in the western Cascade Range, Oregon (Swanston and Swanson 1978) and Van Duzen River Basin, northern California (Kelsey 1977)

Location	Period of record years	Movement rate cm/yr	Method of obesrvation
Landes Creek[1] (Sec. 21 T.22S,R.4E.)	15	12	Deflection of road
Boone Creek[1] (Sec.17 T.17S,R.5E.)	2	25	Deflection of road
Cougar Resevoir[1] (Sec.29 T.17S,R.5E.)	2	2.5	Deflection of road
Lookout Creek[1] (Sec.30 T.15S,R.3E.)	1	7	Strain rhombus measurements across active ground break
Donaker Earthflow[2] (Sec.10 T.1N,R.3E.)	1	60	Resurvey of stake line
Chimney Rock Earthflows[2] (Sec.60 T.1N,R.4E.)	1	530	Resurvey of stake line
Halloween earthflow[2] (Sec.6 T.1N,R.5E.)	3	2,720	Resurvey of stake line

[1] Swanston and Swanson 1978

[2] Kelsey 1977

Table 2.—Debris avalanche erosion in forest, clearcut, and roaded areas (Swanston and Swanson 1976)

Site	Period of record	Area		Number of slides	Debris avalanche erosion	Rate of debris avalanche erosion relative to forested areas
	years	percent	km²		m³/km²/yr	
Stequaleho Creek, Olympic Peninsula, Washington, U.S.A. (Fiksdal 1974):						
Forest	84	79.0	9.3	25	71.8	1.0
Clearcut	6	18.0	4.4	0	0.0	0.0
Road	6	3.0	0.7	83	11,825.0	165.0
			24.4	108		
Alder Creek, Western Cascade Range, Oregon, U.S.A. (Morrison 1975):						
Forest	25	70.5	12.3	7	45.3	1.0
Clearcut	15	26.0	4.5	18	117.1	2.6
Road	15	3.5	0.6	75	15,565.0	344.0
			17.4	100		
Selected drainages, Coast Mountains, S.W. British Columbia, Canada[1]						
Forest	32	88.9	246.1	29	11.2	1.0
Clearcut	32	9.5	26.4	18	24.5	2.2
Road	32	1.6	4.2	11	[1]283.2	25.2
			276.7	58		
H. J. Andrews Experiment Forest, western Cascade Range, Oregon, USA (Swanson and Dyrness 1975)						
Forest	25	77.5	49.8	31	35.9	1.0
Clearcut	25	19.3	12.4	30	132.2	3.7
Road	25	3.2	2.0	69	1,772.0	49.0
			64.2	130		

[1] Calculated from O'Loughlin (1974, and personal communication), assuming that area involving road construction in and outside clearcuts is 15 percent of area clearcut. Colin L. O'Loughlin is now at Forest Research Institute, New Zealand Forest Service, Rangiora, New Zealand.

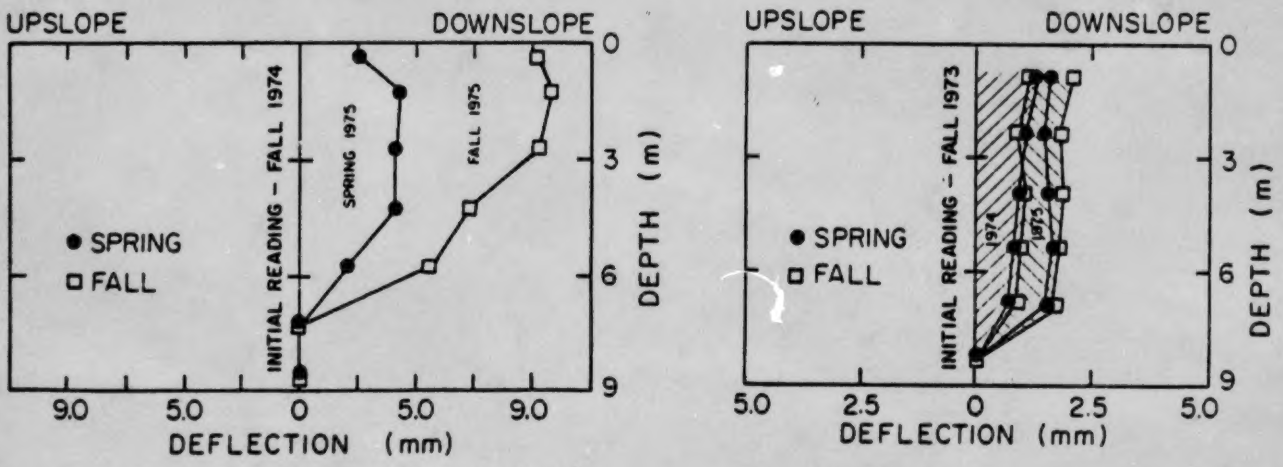
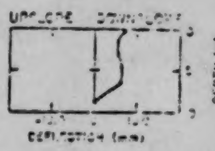
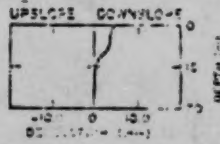
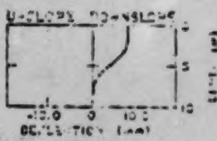
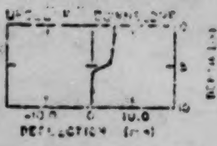
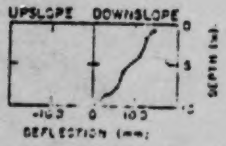


Figure 4. Deformation of inclinometer tubes at two sites in the southern Cascade Range and Coast Range of Oregon, U.S.A.

a) Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil water levels. Note that the difference in readings between spring and fall of each year (dry months) is very small.

b) Baker Creek, Coquille River, Oregon Coast Range, showing constant rate of creep as a result of continual high water levels.

Table .3—Examples of measured rates of natural creep on forested slopes in the Pacific Northwest (Swanston and Swanson 1976)

Location	Data source	Parent material	Depth of significant movement	Maximum downslope Creep rate		Representative creep profile
				Surface	Zone of accelerated movement	
			m	mm/yr	mm/yr	
Coyote Creek, South Umpqua River drainage, Cascade Range of Oregon. Site C-1	Swanston¹	Little Butte volcanic series; deeply weathered, clay-rich, andesitic dacitic, volcaniclastic rocks	7.3	13.97	10.0	
Blue River drainage - Lookout Creek, H. J. Andrews Exp. Forest. Central Cascades of Oregon. Site A-1	Swanston¹	Little Butte volcanic series Same as above	5.6	7.9	7.1	
Blue River drainage, [illegible] Experimental Watershed 10. Site No. 4	McCorison² and Glenn	Little Butte volcanic series	0.5	9.0	—	
Baker Creek Coquille River Coast Range, Oregon Site D-3	Swanston¹	Otter Point formation highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7	
Bear Creek Nestucca River Coast Range, Oregon Site N-1	Swanston¹	Nestucca formation deeply weathered pyroclastic rocks and interbedded, shaley siltstones and claystones	15.2	14.2	11.7	
Redwood Creek Coast Range Northern California Site 3-B	Swanston¹	Kerr Ranch schist sheared, deeply weathered clayey schist	2.8	15.2	10.4	

[1] Douglas N. Swanston, unpublished data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

[2] F. Michael McCorison and L. F. Glenn, data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

Table 4 Characteristics of debris torrents with respect to debris avalanches[1] and land use status of iniation in the H. J. Andrews Experimental Forest[1] and Alder Creek Drainage (Morrison 1975)

Site	Areas of watershed	Period of record	Debris torrents triggerred by debris avalanche	Debris torrents with no associated debris avalanche		Total	Rate of debris torrent occurrence relative to forested areas
	km²	yr	---------------number	-------------------------	------------	km²/yr	
H. J. Andrews Experimental Forest, western cascades, Oregon							
Forest	49.8	25	9	1	10	0.008	1.0
Clearcut	12.4	25	5	6	11	0.036	4.5
Road	2.0	25	17	-	17	0.340	42.0
	64.2		31	7	38		
Alder Creek drainage, western Cascade Range, Oregon							
Forest	12.3	90	5	1	6	0.005	1.0
Clearcut	4.5	15	2	1	3	0.044	8.8
Road	0.6	15	6	-	6	0.667	133.4
	17.4		13	2	15		

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[1] Fredrick J. Swanson, unpublished data on file at Forestry Sciences laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

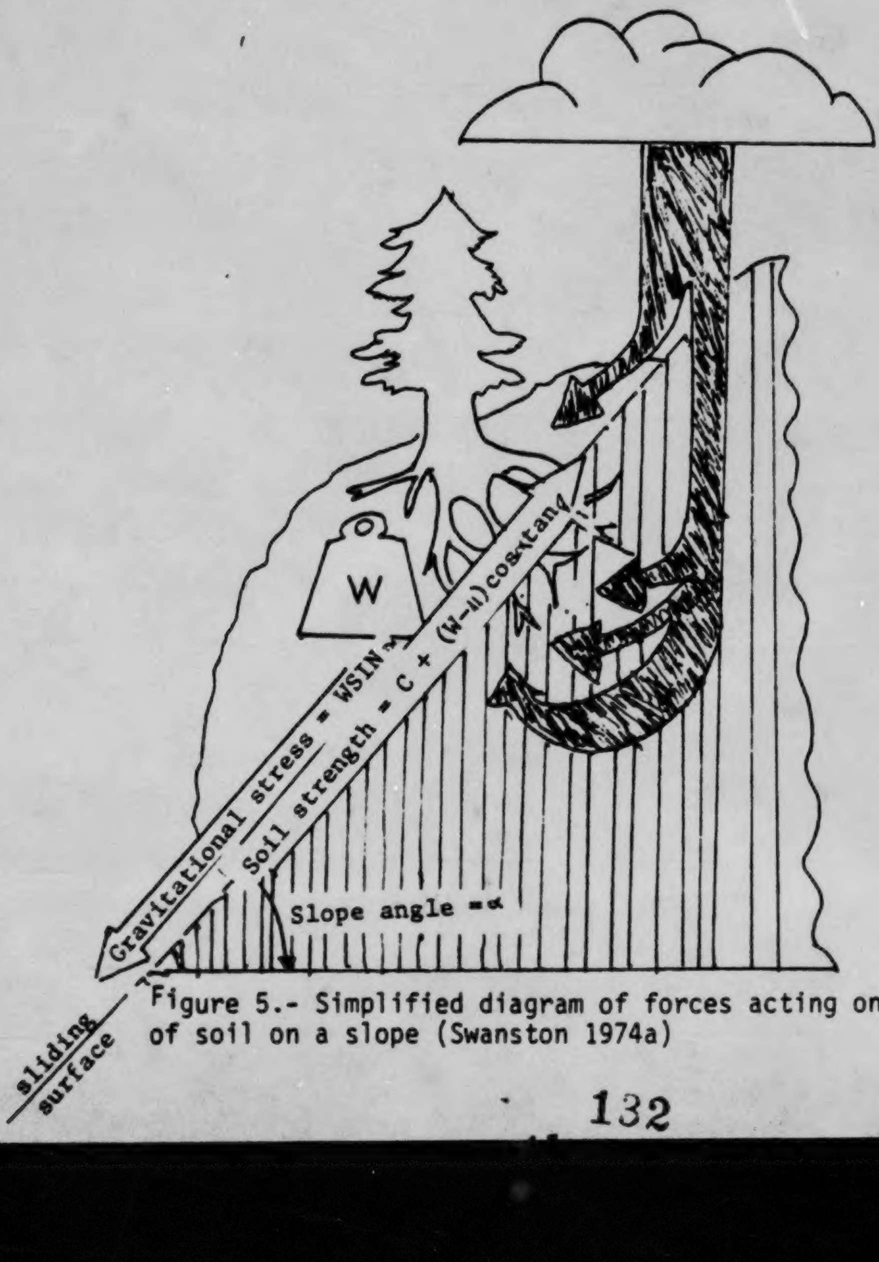
W
Gravitational stress = WSINα
Soil strength = C + (W–u) cosαtanφ
Slope angle = α
sliding surface

Figure 5.- Simplified diagram of forces acting on a mass of soil on a slope (Swanston 1974a)

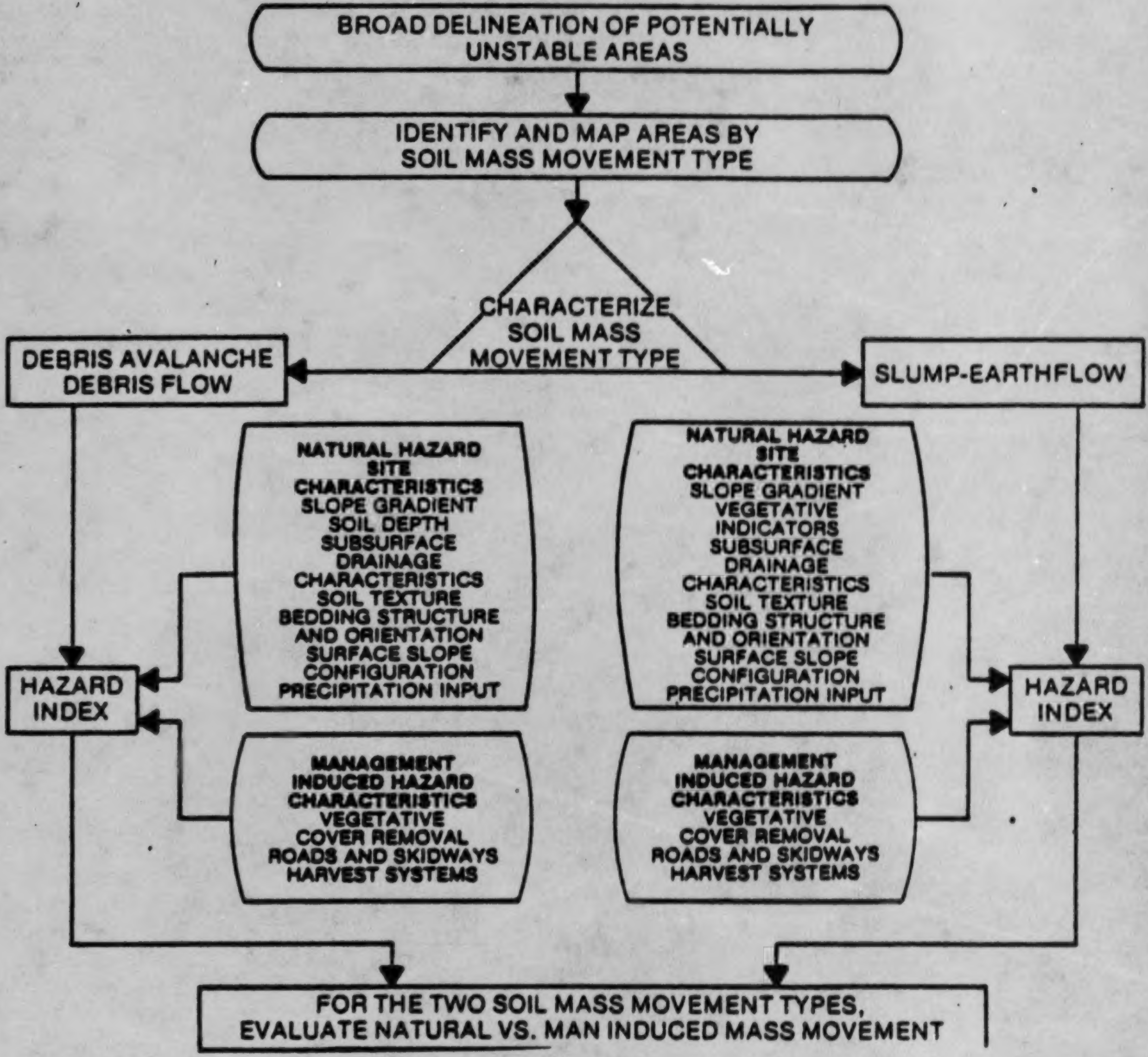
BROAD DELINEATION OF POTENTIALLY UNSTABLE AREAS
IDENTIFY AND MAP AREAS BY SOIL MASS MOVEMENT TYPE
CHARACTERIZE SOIL MASS MOVEMENT TYPE
DEBRIS AVALANCHE DEBRIS FLOW
SLUMP-EARTHFLOW
NATURAL HAZARD SITE CHARACTERISTICS SLOPE GRADIENT SOIL DEPTH SUBSURFACE DRAINAGE CHARACTERISTICS SOIL TEXTURE BEDDING STRUCTURE AND ORIENTATION SURFACE SLOPE CONFIGURATION PRECIPITATION INPUT
NATURAL HAZARD SITE CHARACTERISTICS SLOPE GRADIENT VEGETATIVE INDICATORS SUBSURFACE DRAINAGE CHARACTERISTICS SOIL TEXTURE BEDDING STRUCTURE AND ORIENTATION SURFACE SLOPE CONFIGURATION PRECIPITATION INPUT
HAZARD INDEX
HAZARD INDEX
MANAGEMENT INDUCED HAZARD CHARACTERISTICS VEGETATIVE COVER REMOVAL ROADS AND SKIDWAYS HARVEST SYSTEMS
MANAGEMENT INDUCED HAZARD CHARACTERISTICS VEGETATIVE COVER REMOVAL ROADS AND SKIDWAYS HARVEST SYSTEMS
FOR THE TWO SOIL MASS MOVEMENT TYPES, EVALUATE NATURAL VS. MAN INDUCED MASS MOVEMENT

Figure 6 - Flow chart of the soil mass movement procedure

Table .5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Slope gradient	High >34°	30
	Medium 29° -34°	15
	Low <29°	5
Soil depth	High Shallow soils, <5 ft	3
	Medium Moderately deep soils, 5-10 ft	2
	Low Deep soils, >10 ft	1
Subsurface drainage characteristics	High High density, closely spaced incipient drainage depressions Presence of bedrock or impervious material at shallow depth which restricts vertical water movement and concentrates subsurface flow Presence of permeable low density zones above the restricting layer indicative of saturated flow parallel to the slope Evidence of springs on the slope	3
	Medium Presence of incipient drainage depressions, but widely spaced Presence of impervious material at shallow depths, but no low density zones present Springs are absent	2
	Low Incipient drainage depressions rare to absent No shallow restricting layers present No indications of near-surface flow	1
Soil texture	High Unconsolidated, non-cohesive soils and colluvial debris including sands and gravels, rock fragments, weathered granites, pumice and noncompacted glacial tills with low silt content (<10%) and no clay	3
	Medium Unconsolidated, non-cohesive soils and colluvial debris with moderate silt content (10-20%) and minor clay (<10%)	2
	Low Fine grained, cohesive soils with greater than 20% clay sized particles or mica	0
Bedding structure and orientation	High Extensive jointing and fracturing parallel to the slope Bedding planes parallel to the slope Faulting or shearing parallel to the slope (the stability influence of bedding planes horizontal or dipping into the slope is offset by extensive parallel jointing and fracturing)	3
	Medium Bedding planes are horizontal or dipping into the slope with minor jointing at angles less than the natural slope gradient Minor surface fracturing — no faulting or shearing evident	2
	Low Bedding planes are horizontal or dipping into the slope Jointing and fracturing is minor — no faulting or shearing evident	1

Table 5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures — continued

Factor	Hazard index and range	Weight
Surface slope configuration	**High** Smooth, continuous slopes unbroken by benches or rock outcrops Intermittent steep channels occur frequently with lateral spacing of 500 ft (152 m) or less Perennial channels frequently deeply incised with steep walls of rock or colluvial debris Numerous breaks in canopy due to blow-downs — frequent linear or tear-drop shaped even-age stands beginning at small scarps or spoon-shaped depressions indicative of old debris avalanche-debris flow activity	3
	Medium Smooth, continuous slopes broken by occasional benches and rock outcrops Intermittent, steep gradient channels occur less frequently with a lateral spacing of 500-800 ft (152-244 m) Infrequent evidence of blow-down or past landslide activity	2
	Low Slope broken by rock benches and outcrops intermittent, steep gradient channels spaced 900 ft (275 m) or more apart	1
Precipitation input	**High** Area characterized by rainfall greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity storms capable of generating saturated soil conditions on the slope leading to active pore-water pressure development and high stream flow — area has a high potential for mid-winter or early spring rainfall-on-snowpack events Storm intensities may exceed 6 in/24 hr at 10 yr recurrence intervals or less	12
	Medium Area characterized by moderate rainfall of 20 to 40 in/yr (51 to 102 cm/yr) Storms of moderate intensity and duration are common High intensity storms are infrequent, but do occasionally occur Moderate snowpack, but rain-on-snow events very rare Storm intensities may exceed 6 in/24 hr (15 cm/24 hr) at recurrence intervals greater than 10 yrs.	5
	Low Rainfall in area is low (less than 20 in/yr) Storms infrequent and of low intensity Stored water content in snowpack, when present, is low and only rarely subject to rapid melting	3

Worksheet I

Debris avalanche-debris flow natural factor evaluation form

Index	Slope gradient	Soil depth	Subsurface drainage characteristics	Soil texture	Bedding structure and orientation	Slope configuration	Precipitation input
High	30	3	[✓ 3]	3	3	3	12
Medium	[✓ 15]	[✓ 2]	2	[✓ 2]	[✓ 2]	[✓ 2]	[✓ 5]
Low	5	1	1	0	1	1	3

Factor summation table

Total hazard index	Factor range	Weight
High	Greater than 44	21
Medium	21 - 44	
Low	Less than 21	

Table .6.—Weighting factors for determination of management-induced hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	**High** Total removal of cover — large clearcuts with openings continuous downslope — such removal is sufficient to increase soil moisture levels and reduce strength Broadcast burning of slash	8
	Medium Cover partially removed with slope sections >34° left undisturbed — clearcuts in small patches or strips less than 20 ac (8 ha) and discontinuous on slopes	5
	Low Cover density altered through partial cutting — no clearcutting — no broadcast burning of sites with >34° slope	2
Roads and skidways	**High** High density (>15% of area in roads) on potentially unstable slopes (>28°) — cut and fill construction Roads and skidways located on steep, unstable portions of the slope (>34°) Uncontrolled fills with poor compaction produced by side-casting over organic debris Inadequate cross drainage (poor location; improper spacing and maintenance, size too small for 10 yr storm flow) Lack of fill slope protection of drainage outlets Concentrations of drainage water directed into identifiable unstable areas	20
	Medium Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area) Areas with slopes >34° or with identifiable landslide activity have been avoided or fully benched On potentially unstable slopes >29° skidways and cut-and-fill type construction are limited Ridgetop roads have large fills in saddles Fills, where present, are constructed by sidecasting over organic debris with little controlled compaction Roads generally have adequate cross drains for normal runoff conditions (number and location) but are undersized for the 10 yr storm flow Fill slopes below culvert outfalls protected by rip-rap dissipation structures at potentially unstable sites Major concentrations of water into identifiable unstable areas avoided	8
	Low Very few roads on slopes above 28° — low road density (less than 8% of area) with roads on potentially unstable terrain (slopes between 29° and 34°) predominantly of full bench type — most road locations or construction limited to ridgetops with minimum fills in saddles and lower slopes — adequate cross drains with major water courses bridged and culverts designed for 10 yr storm flow or larger	2
Harvest systems	**High** Operation of tractor yarding, jammer yarding and other ground lead systems on slopes >29° (53%)	3
	Medium No tractor logging — high lead with partial suspension on slopes >29° (53%)	2
	Low Helicopter and balloon yarding — full suspension of logs by any method — yarding by any method on slopes <29° (53%)	0

Worksheet 2

Debris avalanche-debris flow management related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	⑧	⑳	③
Medium	5	8	2
Low	2	2	0

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	31+29 = 60
Medium	21 - 44	
Low	Less than 21	

Table .7.—Weighting factors for determination of natural hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Slope gradient	High greater than 30° (58%)	6
	Medium 15 - 30° (27%-58%)	4
	Low under 15° (27%)	2
Subsurface drainage characteristics	High Area exhibits abundant evidence of impaired groundwater movement resulting in local zones of saturation within the soil mass — short, irregular surface drainages which begin and end on the slope Impaired drainage, indicated at the surface by numerous sag ponds with standing water, springs and patches of wet ground Impaired drainage involves more than 20% of the area	6
	Medium Some indications of impaired drainage, but generally involving less than 10% of the area Active springs are uncommon, infrequent, or contain no standing water	4
	Low No evidence of impaired drainage	2
Soil texture	High Predominantly fine grained cohesive soils derived from weathered sedimentary rocks, volcanics, aeolian and alluvial silts and glaciolacustrine silts and clays Clay sized particle content generally greater than 20% Clay minerals predominantly of the smectite group (montmorillonite), exhibiting swelling characteristics upon wetting	15
	Medium Soils of variable texture including both fine and coarse grained components in layers and lenses The fine grained, cohesive component may contain a clay sized particle content greater than 20%, but clay minerals are predominantly of the illite and kaolinite groups, exhibiting lower sensitivity to changes in stress	10
	Low Soils of variable texture Some clayey soils present but widely dispersed in small layers or lenses	5
Slope configuration	High 40% or more of the area is characterized by hummocky topography consisting of rolling, bumpy ground, frequent benches and depressions locally enclosing sag ponds Tension cracks and headwall scarps indicating slumping are unvegetated and clearly visible Slopes are irregular and may be slightly concave in the upper 1/2 and convex in the lower 1/2 as a result of the downslope redistribution of soil materials Zones of active movement are abundant	5
	Medium 5% to 40% of the area is characterized by hummocky topography Occasional sag ponds occur, but slump depressions are generally dry Headwall scarps are revegetated and no open tension cracks are visible Active slump-earthflow features are absent	2
	Low Less than 5% of the area is characterized by hummocky topography Old slump-earthflow features are absent or subdued by weathering and erosion No active slump earthflow features present, slopes are generally smooth and continuous from ridge to valley floor	1

Table .7.—Weighting factors for determination of natrual hazard of slump-earthflow — continued

Factor	Hazard index and range	Weight
Vegetative indicators	**High**	5
	Phreatophytic (wet site) vegetation widespread Tipped (jackstrawed) and split trees are common Pistol-butted trees occur in areas of obvious hummocky topography (note: pistol-butted trees should be used as indicators of active slump-earthflow activity only in the presence of other indicators — pistol-butting can also occur in areas of high snowfall and is often the result of snow creep and glide)	
	Medium	3
	Phreatophytic vegetation limited to occasional moist areas on the open slope and within sag ponds Tipped trees absent	
	Low	0
	Phreatophytic vegetation absent	
Precipitation input	**High**	18
	Area characterized by high rainfall of greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity, long duration storms capable of generating continuing saturated conditions within the soil mass leading to active pore water pressure development and mobilization of the clay fraction Area has a high potential for rain-on-snow events	
	Medium	10
	Area characterized by moderate rainfall of 20 to 40 in/yr (51 cm/yr to 102 cm/yr) Storms of moderate intensity and duration are common Snowpack is moderate, but rain-on-snow events are rare	
	Low	2
	Rainfall in the area is low (less than 20 in/yr) storms are infrequent and of low intensity and duration Stored water content in the snowpack, when present, is low throughout the winter with no mid-winter or early spring releases due to climatological events	

Worksheet 3

Slump-earthflow natural factor evaluation form

Index	Slope gradient	Subsurface drainage characteristics	Soil texture	Slope configuration	Vegetative indicators	Precipitation input
High	[✓ 6]	6	15	[✓ 3]	5	18
Medium	4	[✓ 4]	[✓ 10]	2	[✓ 3]	[✓ 10]
Low	2	2	5	1	0	2

Factor summation table

Gross hazard index	Range	Natural
High	Greater than 44	3[illegible]
Medium	21 - 44	
Low	Less than 21	

Table .8.—Weighting factors for determination of management induced hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	**High** Total removal of cover or large clearcuts with openings continuous downslope — such removal would be sufficient to increase soil moisture levels and reduce root strength	3
	Medium Cover partially removed — clearcuts in small patches or strips less than 20 acres (8 ha) is size and discontinuous downslope	2
	Low Cover density altered through partial cutting, no clearcutting evident	1
Roads and skidways	**High** High density (>15% of area in roads) cut-and-fill type (balanced) construction Roads and skidways located or planned across identifiable unstable ground Roads crossing active or dormant slump-earthflow features Massive fills or spoil piles on slump benches Inadequate drainage creating concentrations of water at the surface with diversion of surface drainage into unstable areas	7
	Medium Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area in roads), unstable areas features avoided Roads generally have adequate cross drains for normal runoff conditions but are undersized for 10 yr storm flows Diversions of concentrations of water into unstable sites avoided	4
	Low No roads present — if present, predominantly fully benched Road density less than 8% Most road location and construction on ridgetops or in alluvial valley floors Adequate cross drainage with dispersal rather than heavily concentrated surface flow	2
Harvest systems	**High** Operation of tractor yarding, jammer yarding or other ground lead systems causing excessive ground disturbance	3
	Medium High lead yarding with partial suspension and skyline with partial suspension No tractor yarding	2
	Low Helicopter and balloon yarding Full suspension of logs by any method	1

Worksheet 4

Slump-earthflow management related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	③	7	③
Medium	2	4	2
Low	1	②	1

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	38+8 = 46
Medium	21 - 44	
Low	Less than 21	

Runoff Agriculture: Water Harvesting and Water Spreading

Gerald Harwood

(Partially adapted from Fogel, 1975 and Cluff and Dutt, 1975)

Runoff Agriculture

The term runoff agriculture implies the direct use of water that has been collected on a watershed and transported to an irrigation site through streams or channels. Taking advantage of natural processes, it was developed simultaneously with early Middle Eastern civilizations. Runoff agriculture incorporates two important techniques, water spreading and water harvesting. Water spreading involves the direct diversion of rain water from a natural watershed through systems of dikes and channels to an irrigation site. Water harvesting is a further refinement of the process in which precipitation water is derived from a specially treated collection surface. In either situation, the water may be used immediately or stored for the future. While water harvesting and water spreading will be discussed separately in this unit, the reader should be aware of their close relationship. Water harvesting refers to a method of water collection whereas water spreading concerns its distribution. Water harvesting systems used for agriculture must incorporate water spreading techniques.

Early Runoff Agriculture Systems

Irrigation is basically the process of artificially applying water to land for agricultural use. While it was born of early cultures in arid and semi-arid lands, the practice has spread to most parts of the world and has become absolutely essential for the feeding of the earth's burgeoning population. Since rivers and lakes were the major freshwater sources, the earliest irrigation efforts probably consisted of systems of canals for the transport of river water to nearby fields. Natural water channels were enhanced for purposes of drainage and irrigation, giving rise to the development of canals and levees; dams were also constructed for water control and storage.

Biswas (1972) has noted that the earliest of the earth's major civilizations were founded along river banks: the Sumerians of Mesopotamia on the Tigris and Euphates rivers; in India, the Harappans on the banks of the Indus; the the Egyptians on the Nile; and the Chinese on the Huang-Ho river. These civilizations had certain geographical conditions in common: they were located on major rivers, rainfall was scarce, summer temperatures were high and, in each case, they had to deal with problems arising from fluctuations in flow of the rivers upon which they were dependent. The Chinese civilization on the Huang-Ho river developed after 600 B.C.; the other three societies date back some 4,000 years.

Gulhati (1955) and Biswas (1972) have described several early irrigation projects, some of which are more than 4,000 years old. In the valley of the Euphrates and Tigris rivers, the remains of two irrigation canals can be found which are thought to have been used circa 2300 B. C.; one canal, estimated to have been between 30 and 50 feet deep and 400 feet wide, is now part of a modern irrigation system. King Menes, the first Pharoh of the First Egyptian Dynasty, ca 3000 B.C., dammed the Nile and diverted its course through a 12 mile long channel into a lake which stored flood waters for release into irrigation basins during periods of drought. Irrigation systems in China date back to at least 300 B.C. The Imperial Canal, constructed in China around 700 A.D., was 700 miles long and used for both irrigation and navigation.

Ancient irrigation, however, was not restricted to river valleys and lands that could be served by diversion canal systems. Runoff agriculture systems incorporating water harvesting techniques were developed in the Middle East almost simultaneously with river diversion. Water harvesting is extremely simple in concept, involving the collection, conveyance and storage of surface water derived from precipitation runoff. Water harvesting can be done on a large scale such as a watershed or on areas as small as a rooftop. Watersheds may be left in their natural condition or specially treated to enhance surface water runoff.

Water harvesting systems were used by the peoples of the Negev Desert perhaps 4,000 years ago (Evenari, Shanan, Tadmar and Aharoni, 1961). Hillsides were cleared of vegetation and smoothed in order to provide as much precipitation runoff as possible; the water was then channeled in contour ditches to agricultural fields at lower elevations. By the time the Roman Empire extended into the region, this method of farming encompassed more than 700,000 acres and had become quite sophisticated. After the conquest of this land by the Arabs in 630 AD, these farms declined and the technique was gradually forgotten. In the New World, approximately 400 - 700 years ago, people living in what is now the Mesa Verde region of Colorado employed relatively simple methods of water harvesting for irrigation (O'Bryan, Cooley and Winter, 1969).

The use of water harvesting in recent times is reflected in the term "rain barrel" which is still a common phrase language even though such barrels are rarely seen today in the continental United States. The collection and use of runoff from roof tops is a widespread practice in many parts of the world. In the U.S. Virgin Islands, water harvesting is mandated for domestic use. Building codes require that 10 gallons of water storage capacity be provided in cisterns for each square foot of roof surface area. Even the smallest buildings have collection and storage systems; very large catchments have been constructed on hillsides to provide water for hotels and schools. At one time, water so collected was sold to passing ships. The harvesting of rain water for modern agricultural use was pioneered in Australia during the 1920's. Galvanized roof-like structures were built without houses beneath them, solely for the purpose of water harvesting. Alternatively, sections of sheet metal were spiked to the ground for water collection (Kenyon, 1929).

Modern Runoff Agriculture Systems

Requisite Conditions for Runoff Agriculture Systems

Before planning a runoff agriculture system, certain essential conditions must be met by the proposed site. First, there must be a sufficient quantity of surface runoff water available in the proper seasons for crop production. Accordingly, the topography, geology, soil, vegetation and climate must combine each year to give at least a few sudden water flows of usable quantity without the production of flood damage. Secondly, the land on which the runoff water is used must be both suitable for crop production and conveniently located to the runoff area.

The type of farming practiced must make the best use of the water. In general, perennial crops with deep root systems adapt well to runoff agriculture because they can use water stored deep in the soil where it is safe from evaporation.

While there are several variations to runoff agricultural systems, three basic elements are common to all: (1) a water supply produced by a runoff area or a water harvestng system; (2) a water spreading site where the crops are to be grown; and (3) a water distribution system.

The Water Supply

The water supply for runoff agriculture will generally come from a stream channel which is dry most of the time but which flows for short periods following heavy rains or snow melt. Alternatively, the supply source could be a water harvesting catchment. First, it is important to determine whether the watershed area above the spreading site will be capable of furninshing an adequate supply of water. Ideally, the source should be able to provide a prolonged flow at a rate that is large enough to spread well while remaining manageable.

When planning runoff agriculture systems, the first task is to determine whether or not the watershed above the site will be able to furnish an adequate supply of water. It is desirable to have a flow large enough to spread over the irrigation site but not so large as to exceed the capacity of the water spreading system. Accordingly, information is necessary with respect to: (1) the rate of peak flow per second; (2) the total volume of available water in a given period of streamflow; and (3) whether or not such flows will be frequent enough to justify building the system.

Watershed characteristics that influence runoff

Watershed conditions are seldom uniform; instead, they present a great variety of slopes, soils, vegetation, stream patterns and other variables which can affect runoff. It is important to examine the watershed with the following points in mind:

Topography. Observe the slopes and exposed rock formations. If the rock layers or strata are tipped or inclined into the drainage area, conditions should be favorable for good runoff. If the reverse is true, runoff may be very low. On the other hand, a level bedded formation may provide an excellent site.

Note which slopes have the most vegetation. In dry regions, vegetation and water supply are closely interrelated. Where there is more vegetation, there is more soil moisture. Rainfall usually increases with elevation above the surrounding country. The higher the drainage area, the better are the chances for abundant runoff. Great differences in rainfall may occur within short distances. Other things being equal, in the northern hemisphere, northern slopes usually yield the most water, as they are protected from the drying influence of the sun; in the southern hemisphere, this effect will be observed on the southern slopes. Streams with steep gradients tend to carry large amounts of bed load or heavy material ranging from very fine particles to coarse gravel and boulders which roll or slide along stream bottoms during periods of flow.

Close observations of small rills or depressions will indicate whether they carry water frequently. If flows are frequent, the channels will be swept clean excepting for drift material which is plainly water deposited. As a rule, the steeper the slope, the greater the runoff.

If the drainage area consists of many small, narrow valleys with steep slopes at right angles to the streams, the runoff will probably be rapid and of short duration. Terrain consisting of broad, flat valleys, will produce significantly longer runoff periods. Another factor affecting runoff periods and peak flows is the grade of a stream. Long narrow drainages produce longer runoff periods with lower peaks than do relatively wide and short ones.

Rainfall. It is important to study all available rainfall records that may be representative of the drainage area. The distribution of the rainfall, not only by months but also by days, is very important. The frequency of maximum intensity storms is also important. Runoff is usually produced by heavy rains falling within a short period of time. For example, if the average annual precipitation is 8 inches, and half of it usually occurs during June and July, it is desirable to know whether there are 15 days with rain during this period or only 5 in the average year.

Soils. The soils of the runoff area should be carefully examined. Most clay soils absorb water slowly. Shallow soils over clay or impervious rock yield high runoff after the permeable layers become filled with water. Deep sandy soils and soils with good structure will absorb water rapidly and release it slowly. Sandy or silty soils are likely to be erodible, especially on steep slopes. Sometimes soils can be examined in the sides of gullies or cut banks.

Vegetation. Vegetation is an important factor affecting water yield and type of stream flow. Watersheds with a heavy cover of grass, shrubs, or trees seldom produce sudden heavy runoff. Vegetation affects most soils in such a manner as to cause the soil to act as a sponge, in taking up moisture as it falls and then releasing it slowly. This condition is favorable for sustained stream flow.

Vegetation is the most desirable medium of erosion control. Runoff from a drainage area with good vegetation cover will not usually contain enough sediment to overburden a water distribution system. Grass is the best vegetative cover for a watershed used in runoff agriculture; improving existing grass cover will not greatly reduce water yield. Runoff from vegetated drainage areas may carry considerable drift comprised of grass blades, leaves, twigs, and sticks; such debris may be a nuisance to water distribution systems but it is preferable to large volumes of sediment.

Estimation of precipitation runoff

Available runoff records. Runoff records, when available, are the best source of information on water supply, particularly records which are continuous for a 20-year period or longer. The records from gauging stations on reservoirs and streams are sometimes available. Here again, the records are not likely to be reliable unless they cover a period of at least 20 years. It is important to be aware of the fact that many gauging stations are so distant from the drainage area that considerable care must be exercised in using the records. Sometimes, however, if conditions are reasonably similar, records from drainage areas as much as 50 to 100 miles away may be useful.

Determination of peak runoff by the slope area method. If no runoff measurements are available, the slope area formula is commonly used to compute peak discharge. The computation is based upon water marks and drift lines left by high flows observed at several points in a stream channel. A sufficient number of high-water marks must be located along a reasonably straight, smooth portion of the stream channel in order to permit determination of the surface slope at the time of peak runoff. Cross sections of the channel are then determined, usually by leveling. With an estimate of the channel roughness, the peak flow is computed by either the Chezy or the Manning formulas. Accurate estimations of flow are difficult to obtain by this method, as the flow durations are not known. If flow durations can be estimated from available runoff data, a simple triangular hydrograph can be used to estimate the volume of flow.

Collection of Precipitation by Water Harvesting

Elements of Water Harvesting Systems

Water harvesting systems may be defined as artificial methods whereby precipitation can be collected and stored until it is beneficially used. The system consists of a catchment made more impervious by artificial means than it was in its natural state and, unless the water is to be immediately used, a storage facility for the harvested water.

Water Collection. There is no single method of treating catchments to increase runoff that is universally applicable. Each site must be individually evaluated in order to determine the optimum treatment that will produce water from a given site for a particular use.

Numerous factors must be considered in the design of a water harvesting system, including the amount of runoff to be expected from storms of various magnitudes, the ratio of runoff to precipitation or runoff efficiency, and the effect of the selected treatment on the quality of the water. The runoff efficiency is highly variable, depending upon storm intensity, the permeability of the surface of the watershed, the degree of saturation of soil of the watershed, etc. Precipitation is a random variable; the selection of a particular treatment to induce runoff and the size of the catchment should reflect the uncertainty of precipitation and runoff.

For almost all treatments, there is a minimum threshold amount of precipitation required to saturate the catchment surface; below this amount, virtually no runoff occurs. However, once this threshold has been exceeded, the relationship between storm precipitation and runoff will be essentially linear. The Soil Conservation procedure is one method that can be used to relate runoff to rainfall.

A catchment can be made more impervious using the following methods: (1) land surface alteration, (2) chemical treatments, (3) soil cementation treatments, and (4) ground cover modification. In land alteration, runoff can be increased by (1) clearing and smoothing, (2) shaping, and (3) compaction. The two basic types of chemical treatment are the use of water repellents such as silicones and clay dispersants such as sodium salts. Soil cementation treatments include the mixing of asphalt, cement, resins, and polymers into the soil. Ground covers that have been used for catchment construction can be classified as (1) exposed membranes including butyl, plastic, and asphalt, (2) covered membranes, generally utilizing gravel to cover plastic sheeting, (3) reinforced cement-mortar coated plastic, (4) sheet metal, (5) concrete, (6) reinforced asphalt, and (7) asphalt planking.

Water Storage. Various methods of storage have been used with the above methods of catchment construction. These methods include (1) above-ground tanks and (2) lined reservoirs.

The above-ground tanks have been constructed from (1) steel, (2) reinforced concrete, (3) metal grain bins with flexible liners, (4) butyl bags, (5) wire reinforced stucco, and (6) railraod tank cars and other types of surplus tanks.

The earth reservoirs have been sealed with various types of membrane liners and by mechanical and chemical treatment. The membranes that have been used include (1) plastic and butyl rubber sheeting, (2) unreinforced and reinforced asphalt membranes, and (3) reinforced cement-mortar coated plastic. Mechanical and chemical treatments include (1) mechanical compaction with and without the use of a compacting agent such as enzymes, (2) clay dispersants which are also sometimes compacted, (3) water repellants, (3) polymers such as SS-13, and (5) bentonite (Boyer and Cluff 1972).

Evaporation and Seepage Control. Evaporation and seepage control are needed in order to successfully store harvested water. The methods used in achieving this control are generally dependent on the size and function of the storage facility. Frequently, the same materials are used for both the catchment and the reservoir because seepage control and runoff inducement must both function so as to reduce the entry of water into the soil. Like the catchment, the size of the reservoir must anticipate the precipitation and runoff variability of the particular site. In some instances, evaporation has been controlled by use of chemicals such as long chain alcohols, by use of floating and suspended covers of butyl rubber and plastic sheeting on small tanks, and by completely filling the tank with rock.

Integration of Water Harvesting and Water Spreading

Integrated water harvesting systems can be designed. In these systems, storage of the water may be less important than catchment and distribution. The method chosen for treatment of the watershed must be one that will provide water of a quality that will permit growth of the planted seedlings. Strip planting and water spreading may also be important elements of the system. Water spreading systems can be integrated with strip planting and water harvesting in desert farming; for example, a series of terraces can be used to shed water onto a neighboring strip of productive soil.

These may be tiered up a hillslope, but on level terrain, an artificial slope can be made by mounding the soil between the strips. The watershed section can, alternatively, be left in a natural state, cleared of vegetation, planted with range grasses or treated by some water harvesting technique that will induce runoff. These systems have been discussed in some detail by Fogel (1975).

Development of Modern Water Harvesting Techniques

Since the 1950's, the technology of water harvesting has developed variety and sophistication. In Australia, "roaded" catchments, based upon the concept of compacted earth, were constructed over thousands of acres in order to collect water for agricultural purposes. In a roaded catchment, the soil is graded into a series of parallel ridges, having gentle slopes that permit water flow into the ditches that separate them. The ditches then channel the water to storage areas, or the water may be used directly at the site (see Myers, 1975). Detailed discussions of roaded catchments may be found in Firth (1975).

In the United States, catchments were built in the 1950's out of sheet metal for watering livestock. Also during this period, experimentation was undertaken with plastic and artificial rubber membranes, for the construction of both catchments and of reservoirs (Lauritzen, 1960). Since then, butyl rubber catchments have been installed in many areas. More than 300 catchments in the state of Hawaii have been constructed of this material (Myers, 1975). Chiarella and Beck (1975) have reviewed the use of water harvesting techniques on Indian reservations in the western United States. A number of experiments have been attempted over the years, not all have been successful, but some have worked well. One catchment at Shongopovi, on the Hopi reservation, has provided supplemental domestic water since the early 1930's; this catchment was constructed with very little disruption of the natural topography. On the Navajo reservation, butyl rubber catchments and storage bags are successfully used by stockmen. A concrete catchment is being constructed on coal mine spoils on the Black Mesa to test the feasibility of water harvesting for agricultural purposes on the spoils McBride and Shiflet (1975) have described the construction, placement and use of larger catchments in the Safford district of southern Arizona.

In 1961, Myers (1961) suggested the waterproofing of the soil itself to serve as a catchment structure. His group tested materials that imparted hydrophobic properties to the soil, thus decreasing its permeability to water. Materials tested included sprayable asphaltic compounds, plastic and metal films bonded to the soil, soil compaction and dispersion, and field fabricated asphalt and fiberglass membranes (Myers, 1975). In Israel, Hillel has investigated the potential of oil and other water repellants for soil treatment, but most of his research has been along the lines of soil smoothing and crusting (Cooley, Dedrick, and Frasier, 1975).

Aldon and Springfield (1975) have tested the applicability of water harvesting techniques for the growing of shrubs on coal strip mine soils in New Mexico. They found that treatment of the ground with paraffin increased water runoff and the growth of two month old saltbush and Siberian peashrub transplants; the soil moisture content of treated plots was increased by about twenty percent. A number of studies have been done on the use and suitability of water harvesting as an agricultural technique. Fogel (1975) has discussed various aspects of runoff agriculture, including techniques for computing runoff, and water spreading systems. Morin and Matlock (1975) have computer modeled a system of water harvesting and strip farming, based upon data collected in the Tucson area. Their results suggest that while conventional irrigation techniques produce greater crop yields, significant short season grain sorghum crops could be produced from harvested water in 4 out of 5 years. Further discussion of agricultural applications of water harvesting may be found in Fangmeier (1975), Jones and Hauser (1975), Luebs and Laag (1975) and Rawitz and Hillel (1975).

There is considerable variation in the cost longevity and efficiency of the above methods of catchment and storage construction. The above systems would need to be evaluated for each site in order to select the optimum system. Some of the systems to be discussed in the following section have been developed and/or tested at the Water Resources Research Center, University of Arizona, over the past fifteen years. In general, these systems are among the most economical of those mentioned above. These water harvesting systems were designed to (1) provide a dependable supply of stock water, (2) provide a high quality water for domestic and industrial supplies, and (3) extend agriculture into lands presently uncultivated due to lack of water.

Water Harvesting Catchments Tested at the University of Arizona

Some of the more economical materials mentioned in earlier sections of this chapter have been tested in the Water Harvesting Program at the University of Arizona; however, the most expensive materials, such as sheet metal, concrete, asphalt panels, and asphaltic pavements, were not tested. The results from small plots using exposed unreinforced asphalt membranes have shown that, although relatively inexpensive, this method is undesirable due to cracking caused by oxidation, plant germination, and swelling and shrinking of the soil subgrade. Myers, Frasier, and Griggs (1967) have experienced these difficulties in their work with exposed, unreinforced membranes. Based on the results of small plot tests, economics, and experience of other researchers, large scale testing at the University of Arizona has been limited to the following treatments: (1) compacted earth, (2) sodium, (3) gravel covered plastic, and (4) reinforced chip-coated asphalt catchments. A discussion of these catchments follows. [Note: All cost estimations presented in the following section are in 1972 U.S. dollars, and unless otherwise noted, are based upon construction methods used in Arizona.]

Compacted Earth Catchments (CE)

The Public Works Department of Western Australia initiated in 1948 a program of construction of Roaded Catchments (Carder 1970). These catchments consisted of clearing, shaping, and contouring to control length and degree of slope and compacting with the aid of pneumatic rollers. An estimated 2500 roaded catchments have been installed principally to supply water for livestock use (Hollick 1973). These average approximately two acres in size. There are also 21 roaded catchments totaling 1745 acres (706 hectares) and ranging in size from 30 to 175 acres (12.1 to 70.8 hectares) presently being used to furnish domestic water for small towns in Western Australia.

This relatively large scale use in Australia of the compacted earth catchment attests to their utility. A one acre (0.4 hectare) compacted earth catchment was constructed in the spring of 1970 at Atterbury Experimental Watershed located near Tucson, Arizona. A design similar to those in Australia was used. Two 300 foot (121.9 meters) long drains spaced 50 feet (15.2 meters) apart collected water from 25 foot (7.6 meters) long slopes. The drainage channels were covered with plastic and gravel to prevent erosion and water loss. The catchment was shaped by a grader following a one-half inch (1.27 centimeters) rainfall. The plot was then smoothed using a tractor-drawn rotary rock rake (Cluff et al. 1972). This proved to be an excellent method of smoothing. Following an additional one-half inch (1.27 centimeters) of precipitation, the plot was compacted using a 26 ton (23.6 metric tons) vibratory drum roller. The drainage channels were also lined at this time. The total cost of the catchment was approximately $250 including wages at $3.50 per hour. The cost would be more if the catchment site were more remote, unless several catchments were installed at one time. For large catchments, the cost should be less than $150 per acre ($370.60 per hectare), the cost being primarily dependent on the cost of clearing and shaping. The smoothing and compaction costs on a large plot would be relatively low. There has been little maintenance since the plot was installed. Carder (1970) indicated that maintenance would consist primarily of weed control, and if care were taken not to disturb the surface while controlling weeds, the road surface should improve with age.

During the 18-month project period, a total rainfall of 19.73 inches (50.11 centimeters) occurred. The compacted plot yielded 6.96 inches (17.68 centimeters) or 35.3 percent of the total rainfall. This represented an increase of 4.86 inches (12.34 centimeters) over the water yield from a control plot. The amount of precipitation required to initiate runoff was about 0.20 inches (0.51 centimeters).

Assuming a life of 20 years, an interest rate of six percent, and an efficiency of 35 percent in a 12-inch (30.48 centimeters) rainfall area, the cost of water harvested from the compacted plot would be approximately 18 cents per thousand gallons ($0.48 per cubic meter). This price does not include weed control costs. Economy of scale would reduce this cost even further on larger catchments.

Sodium treated catchments

Results from previous research (Kemper and Noonan 1970; Cluff et al. 1971) indicate that small amounts of sodium, when applied to the surface of desert soils where there is little or no vegetation, will cause a dramatic reduction in infiltration rate. The effect, however, has been found to be temporary. Sodium does cause a clay migration from the surface. Clay lenses have been created in the laboratory and the field through the use of a relatively heavy treatment of sodium chloride. These clay lenses have been found to be migratory in the sandy loam soil (clay content = 11 percent) at Atterbury Experimental Watershed. When the lenses are close to the surface, they have a large effect on runoff. As the lenses move down in the soil profile, the effect becomes negligible.

The application of a relatively light treatment of sodium (up to 15 percent exchangeable sodium in the surface inch) to a grass-covered soil does not result in a significant change in infiltration rate. The maintenance of a grass cover seems to be incompatible with the use of a light treatment of sodium chloride to increase runoff.

Results have indicated that sodium chloride can be used in increasing runoff where the soil is bare. Periodic disking and smoothing of the soil surface may be needed along with retreatment of sodium chloride in order to maintain a low infiltration rate. The disking may also be required to return the clays to the surface. This method of treatment would require shaped catchment areas to minimize the length and degree of slopes so that erosion would not be excessive.

Perhaps the most effective use of sodium chloride is in conjunction with the compacted earth catchment. The sodium not only renders the catchment more impervious but is an effective way to control weeds. Weeds are the major maintenance problem in compacted earth catchments. The Compacted-Earth Sodium-Treated (CEST) Catchment has been field tested on a one acre site at Page Experimental Ranch. The catchment was prepared in the spring of 1971 in the same way as the CE Catchment at Atterbury Experimental Watershed. After shaping, the plot was rototilled to destroy soil structure. Five tons of granulated salt were then added using a fertilizer spreader. The granulated salt was mixed into the upper two inches of soil and the soil surface smoothed using the rotating tractor-drawn rock rake. Following a 0.4 inch (1.01 centimeters) rainfall, the catchment was compacted with a drum roller. The total cost of the CEST Catchment was approximately $450. Economy of scale should reduce the cost of this catchment to less than $350 per acre. This catchment was constructed to serve a dual purpose. Grapes and deciduous fruit trees have been planted in the drainageways. Water is stored both in the soil and in a 150,000 gallon storage tank where it is available for use during dry periods. Thus, the catchment can produce both food and water. This type of dual system should be more acceptable to the general public than bare catchment areas. The efficiency of this system neglecting soil-stored water has been greater than 50 percent of the total rainfall.

The Page CEST Catchment is located in a 16-inch (40.64 centimeters) rainfall area. Based on a 25-year amortization period and an interest rate of six percent, the cost of excess water produced at this catchment is $0.16 per thousand gallons ($0.42) per cubic meter) or $0.20 per thousand gallons ($0.0529 per cubic meter) in a 12-inch (30.48 centimeters) rainfall area. Economy of scale should reduce this cost still further on large size catchments. The above cost figures do not reflect the value of crops produced from the soil stored water. These costs are similar to those given for the CE Catchment at the Atterbury Experimental Watershed. It should be noted that the CE Catchment would be impractical at Page Ranch due to weed and grass problems.

Gravel covered plastic (GCP)

The use of exposed plastic for water harvesting has been unsuccessful (Cluff 1971) due to ultra-violet induced oxidation, wind, and mechanical damage. The use of gravel protects the plastic from sunlight and wind. Gravel covered plastic catchments were first installed at the University of Arizona in December of 1965. The six-mil (0.015 millimeters) polyethylene plastic in early installations is still in excellent shape.

In order to reduce costs of the gravel covered plastic catchment, two different types of automated installation were developed. One type was a plastic laying gravel chute that fits on the back of a dump truck. By means of the chute, plastic could be laid down and covered in one installation (Cluff 1968).

A more controlled method of installation of GCP catchments can be attained through the use of a self-propelled chip spreader modified in the manner shown in Figure 1. Where specialized gravel spreading equipment is not available, the catchment has been installed at a rate of 2000 ft2 (185.8 square meters) per hour using a front-end loader and a crew of five.

Large areas of the world have sufficient gravel in the upper soil profile to cover the plastic. Because of this, a machine was developed that would extract the gravel from the soil, lay plastic, and cover the plastic with the extracted rock. Considerable research effort was expended in the successful testing of this type of machine which was called the Gravel Extracting Soil Sifter (GESS) (Cluff et al. 1971).

A schematic of the GESS is given in Figure 2. In areas where the GESS is not available or for remote sites, hand labor can be utilized.

The efficiency of a graveled plastic catchment is given by:

$$E = 100 \sum_{1}^{n} (P_i - L)/(\sum_{1}^{n} P_i + \sum_{1}^{m} S_j)$$

where L = amount of water trapped by the gravel cover

m = total number of storms which have a rainfall total less than L

n = total number of storms which have a rainfall total greater than L

E = efficiency of the plastic catchment for period when n + m storms occur

P_i = precipitation total of ith storm whose total is greater than L

S_j = precipitation total of jth storm whose total is less than L.

The loss L has been found to stabilize at approximately 0.11 inches (0.28 centimeters) for a properly constructed catchment. In a rainfall regime similar to Tucson, the efficiency would be approximately 70 percent.

A catchment is properly constructed if the plastic is covered with the minimum size and depth of gravel needed to provide a complete cover and resist erosion. Figure 3 contains the results of a study which indicates what this minimum cover would be for different slopes (Cluff et al. 1971). This figure shows that on a 10 percent slope 100 feet (30.48 meters) long, a one-half inch cover of 3/16 to 3/8 inch (0.48 to 0.95 centimeters) gravel will withstand an 18-inch (45.7 centimeters) per hour intensity rainfall. In contrast with the CE and CEST catchments, the GCP Catchment produces sediment free water, a primary consideration in domestic supplies. The cost depends on the method of installation. In general, it would be approximately $1000 per acre ($2475 per hectare) for large catchments installed with an improved version of the GESS using ten mil (0.0254 millimeters) polyethylene plastic. The use of imported gravel would increase the cost to over $1500 per acre ($3713 per hectare). The projected life of a properly constructed and maintained GCP catchment is twenty-five years. With a 70 percent efficiency and a 6 percent amortization rate, the cost of water would be $0.34 per thousand gallons ($0.089 per cubic meter) in a 12-inch (30.48 centimeters) rainfall zone.

Chip-coated reinforced-asphalt catchments

Frasier, Myers, and Griggs (1970) have developed the fiberglass reinforced asphalt catchment. Several of these catchments have been field tested in Arizona. Work at the University of Arizona in the area of reinforced asphalt catchments have centered around the use of plastic, both polyethylene and polypropylene, as the reinforcement material. The treatment consists of a prime coat of emulsified asphalt followed by a layer of four mil (0.0102 millimeter) polyethylene sheeting or polypropylene matting, which is then immediately covered with a top coat of emulsified asphalt and 1/8 to 3/16 inch (0.32 to 0.48 centimeters) chips. This Asphalt-Plastic Asphalt-Chip coated (APAC) catchment has many good features. It requires approximately one-third the amount of gravel as a GCP Catchment. The treatment should work on any soil type since the plastic reinforcement prevents cracking. Treatment can be completed at one time. No curing time is needed during construction. The plastic should last at least 25-30 years if the catchment is properly maintained. Retreatment would be made by sweeping loose chips from the surface and laying down a new asphalt and chip protective coating. Based on the use of similar treatments in the roofing industry, retreatment would probably be needed every 10 to 15 years. Results from small plots indicate the catchment will cost at least twice as much as the GCP Catchment but will have an efficiency from 90 to 95 percent. This treatment has sufficient merit, and large scale testing is planned.

Water Storage Methods Compatible with Water Harvesting

Catchments Tested at the University of Arizona

In general, the water storage techniques tested at the University of Arizona have been related to stock water supplies and consequently are limited in size. The basic treatment would also be suitable for larger reservoirs, with the possible exception of the rock-filled tank or those tanks utilizing the suspended cover for evaporation control. The seepage and evaporation control methods outlined here can also be used on existing or new reservoirs that are filled from other sources of water.

Plastic-lined rock-filled reservoir

The construction of this tank was prompted by the availability of commercial rock pickers which make the collection of rock for small tanks economical. Although decreasing storage by over 50 percent, the rock greatly reduces evaporation loss and practically eliminates any chance of mechanical damage including vandalism.

The tank is first excavated, then the surface is raked smooth. Two or three layers of ten mil (0.0254 millimeters) polyethylene plastic is then laid down and covered with used rubber tires. The tires are filled with silty clay cover material to reduce the significance of any holes that may inadvertently occur in the plastic. The tires protect the plastic liner as rocks are added to the tank. In the United States, used rubber tires can be easily obtained at no cost. In areas where used tires are difficult to obtain, a 12-18 inch (30.48 to 45.72 centimeter) layer of soil on slopes less than 1:3 or a reinforced coat of cement-mortar could be used on the tank to protect the plastic. Three rock-filled tanks have been constructed in Arizona using a rotary drum commercial rock picker in areas containing sufficient rock to make the system economical. The cost is dependent upon the site and method of collection of the rock (Cluff et al. 1972). The tanks were constructed for a cost of approximately $2300 for 25,000 gallons (94.6 cubic meters) net storage with $1600 expended for the filling of the tank with rock. A reel-type rock picker was tested in connection with the construction of the above tanks. These tests indicated that the use of this type of picker should reduce costs by 50 percent.

The rock-filled tank is very compatible with the GCP Catchment. The larger rock can go into the tank with the smaller rock being used to cover the plastic on the catchment. A schematic of a water harvesting system of this type is shown in Figure 4.

Plastic-lined concrete-coated or earth-covered

The various methods of seepage control were outlined in the introduction. Plastic lining, if properly covered, offers a positive method of seepage control that is very competitive with other methods. Tests have indicated that a layer of silty soil, or a three-quarter inch (1.90 centimeter) layer of wire mesh reinforced cement-mortar will greatly reduce the seepage loss through holes that may inadvertently be placed in the plastic liner (Boyer and Cluff 1972). The reinforced mortar coating is placed directly on the plastic and has proven to be an effective cover to use on steep slopes. This coating may either be placed using gunnite equipment or can be hand plastered. The cost of this cover is less than twenty cents per square foot ($2.15 per square meter).

In order to reduce the cost of installation on larger reservoirs, the same equipment developed for laying graveled plastic catchments can be used for laying and covering of plastic liners with soil (Cluff 1968). On smaller tanks, of the size used for stock purposes, the soil covering is generally installed using hand labor. A tank using a covering of soil in the bottom and reinforced mortar on the sides is shown in Figure 5. The economy and strength of the reinforced mortar covered plastic makes it practical to construct a walk-through cattle trough that is directly connected to the tank. This design avoids the need for a float valve which is subject to malfunction and vandalism. The use of the mortar covering also makes it possible to run water directly from the catchment into the tank, thus avoiding any chance of stoppage.

A Coupled-Expanded-Polystyrene Asphalt-Chipcoated (CEPAC) Raft can be used for evaporation control (Cluff 1972). This system, first tested in the spring of 1972, is essentially 100 percent effective in preventing evaporation loss for the area covered. Any size of polystyrene sheets can be coupled together. Those tested at the University of Arizona have been primarily one inch (2.54 centimeters) thick, four by four foot (1.62 x 1.62 meters) sheets. These sheets are coated with emulsified asphalt and immediately covered with 1/16 to 1/8 inch (0.16 to 0.32 centimeters) chips. The sheets are coupled together using a coupler made out of two short lengths of slotted 1-1/2 inch (3.81 centimeters) PVC pipe. An outer frame of 1-1/4 inch (3.17 centimeters) PVC pipe filled wih water provides a protective bumper for the rafts which have been constructed up to 1600 square feet (148.6 square meters). These rafts can be coupled together to cover as large a body of water as desired. The cost of this system is less than ten cents per square foot ($1.07 per square meter).

A suspended cover of butyl or reinforced plastic would be recommended (Cluff et al. 1972) for smaller tanks used for domestic control in which it is desirable to keep out foreign material or eliminate algae growth.

Sodium treated reservoirs

When there is sufficient clay in the soil and the incoming water is higher in sodium than calcium, the use of sodium salt is the most economical treatment for seepage control. The 150,000 gallon (567.8 cubic meters) tank at Page Ranch, constructed in connection with the salt treated catchment, was sealed in 1971 with sodium chloride at the rate of five tons (11.20 metric tons per hectare) per acre. The seepage loss at the tank appears to be insignificant, and due to the fact that the incoming water has more sodium than calcium, the life of the seal is indefinite. Evaporation is controlled at the Page Ranch tank through the use of CEPAC Rafts.

Discussion of the Economics of Water Harvesting Systems

Table 1 gives a summary of the costs and estimated life of the catchments developed at the University of Arizona. Each site and potential water use should be examined in order to determine which catchment and method of storage to use.

The use of the CE and CEST Catchments are limited to areas where soil conditions are favorable. Both the CE and CEST Catchments should not be built where soils are difficult to compact. Tests to date have indicated that clay content should not be less than five nor greater than 35 percent. For soils with the higher clay content, it would also be important to have more sand than silt, otherwise erosion problems would be unsolvable.

Water produced from a CE or CEST Catchment contains considerable sediment. In the case of the CEST Catchment, this sediment is finely dispersed and will remain in suspension. Although salt treated, the water from a CEST Catchment has less than 500 parts per million total salinity and can be used for most purposes including agriculture. Although more expensive, the CEST Catchment is generally preferred over the CE Catchment since the sodium not only increases the efficiency of the catchment but also serves as an herbicide which reduces maintenance costs.

A sodium treated tank would probably be the best to use in conjunction with a CE or CEST Catchment. Periodic retreatment of the tank may be necessary with a CE Catchment.

A graveled plastic catchment should be considered where gravel is economically available, the soil condition is not suitable for a CE or CEST Catchment, and/or a sediment-free water is desired. Generally, a plastic-lined reservoir would be used in conjunction with the GCP Catchment. A rock filled tank should be considered with the GCP Catchment if there is sufficient rock in the area and vandalism is a problem. Otherwise, a CEPAC raft covering would be recommended for evaporation control, unless the water were to be used directly for domestic use. In the latter case, a suspended cover would be recommended.

The APAC system would be used in areas where (1) soil or gravel conditions are such as to make the CE, CEST or GCP Catchments impractical and/or (2) rainfall and/or storage considerations were such that a high efficiency would be needed to maintain a firm water supply. In general, the same type of storage system used for the GCP Catchment could be used for the APAC system. The size of the storage reservoir could be reduced due to the higher efficiency of the APAC system.

Although more research is needed, costs of installation of water harvesting systems have been greatly reduced through application of modern techniques and methods described in this paper. Water harvesting should be considered whenever new water supplies for domestic and livestock use in developing arid and semiarid lands are needed. If the cost is low enough or the value of the crop is high enough, the water harvesting systems described in this paper can also be used to develop new agricultural lands where water is presently unavailable.

The Waterspreading Site

As stated earlier, the basic requirements for runoff agriculture are (1) a watershed that provides enough water to mature a crop and (2) a site suitable for crop production. Numerous favorable and adverse factors must be weighed against each other to determine whether a site is feasible, or to compare one site with another. An evaluation of these factors is also needed to determine the design of the distribution system. Some of the principal factors are discussed in the sections that follow.

Water supply factors to consider

Both volume and frequency of flow are important. While one flow per year may put sufficient moisture into the soil to produce a satisfactory crop, frequent floodings will naturally produce more yield. A small volume (especially if combined with infrequent flow) may not be worth the cost of diversion. A large volume may be too difficult to handle or too much for the size of the available spreading area. In this area, provision must be made to bypass the excess water.

The proper depth of water on the crop-growing area or rate of water application is also an important factor in planning the system. The decision will depend on the water supply, the infiltration and penetration characteristics of the soil, the tolerance of the plants to inundation and the normal season of available water.

For agricultural crop production, the distribution of rainfall events throughout the growing season is crucial to a successful harvest, particularly for the shallow-rooted crops. These crops require water more frequently than those having deep roots. The depth of application per runoff event can be balanced against the relative sizes of the runoff-producing and the crop-growing area. There is no alternative, however, to a scarcity of rainfall events.

For forage production, where surface and internal drainage on the spreading area are good and the water supply abundant, applications up to 300 mm in depth over the area are not too much, if a flow can be expected only once or twice during the growing season. If water is scarce and the area suitable for spreading is greater than the water supply (as is frequently the case), the application of 75 to 150 mm when available may produce more feed than heavier applications on a smaller area.

In connection with water supply, water quality is a factor that must be considered. If the water contains excessive amounts of dissolved solids, it may be unfit for spreading, and in a few years may ruin the soil on the spreading area. If the water supply is suspected of containing harmful salts, analyses should be made to determine if the quantity exceeds allowable tolerances.

Sedimentation factors to consider

Frequent and heavy deposits of sediment may interfere with the effective operation of the system. Such deposits will retard plant growth and may kill the younger plants. Even if the sediment is not excessive in amount, it may be made up of fine materials that will clog the soil pores on the cultivated area and in time reduce the water intake.

If the water coming to the proposed crop-growing site is on a steep gradient and flowing at high velocity, it may be carrying a large quantity of sediment. Most of this load will be dropped when the velocity is checked. Such a quick and heavy deposit of sediment in one place is a distinct disadvantage and must be avoided.

If sediment of high silt content is deposited slowly, it may be beneficial rather than harmful. The spreading water tends to deposit the sediments in a gently sloping plane which fills the low spots and small gullies and other irregularities. Silt deposited in such a manner actually improves the site for spreading purposes. The silt also adds to the soil depth and thus generally improves growing conditions.

Unlike most types of sediment basins, a waterspreading system can function indefinitely without the loss of expensive storage capacity. As sediment accumulates, the height of the dikes can be increased and the storage capacity restored and enlarged. Rapid and heavy sediment accumulation, however, is usually indicative of serious soil erosion conditions in the drainage area upstream, and no time should be lost in applying corrective measures.

Site factors to consider

The ideal site on which to spread runoff water for crop production is a broad, smooth gently sloping plain whose soil is a deep fertile loam.

Runoff agriculture requires a deep soil that can store water between rains. It works best for deep-rooted crops such as trees and shrubs, which can tap stored water and depend less on frequent rainfall. In contrast, annual crops need rain at the beginning of the growing season and usually at intervals thereafter. The method is enhanced by plant varieties able to withstand intermittently wet and dry soil.

Environmental prerequisites include:

1. A minimum mean precipitation of 80 mm per rainy season if the rainy season coincides with the cold period of the year, more if it occurs during summer when evaporation is greater.
2. Soils in the crop-growing areas with high water-storing capacity.
3. Not more than 2 to 3 percent salinity in the cultivated soil.
4. A minimum of 1.5 m of soil depth in the cultivated area (unless water-storage facilities are available).

The Water Distribution System

Several runoff water distribution systems exist from simple terraces to complex diversions. The selection of a particular one will depend on the site factors encountered and on the crops to be irrigated with the harvested water. Usually range and pasture lands use a system in which water is diverted from a natural course onto the land by a system of diversion dams and spreader dikes. Other crops, such as fruits, barley, sorghum and millet, can use a similar waterspreading system or a technique known as desert-strip farming.

Waterspreading

In arid regions, the limited rainfall usually falls during short, intense storms. The water swiftly drains away into washes and gullies and is lost to the region. Sometimes floods occur often to areas untouched by the storm. Waterspreading is a practice of deliberately diverting the floodwaters from their natural courses and spreading them over adjacent floodplains or detaining them on valley floors. The wet floodplains or valley floors are then used to grow forage or cultivated crops (Figures 1 and 2).

The simplest waterspreading system is a small earth dam that may be less than one meter high and five meters long across a minor water course. If the land slopes away from such streams on either side, a number of these simple structures may spread water on a considerable area. This type of structure, but with slightly larger dams, may be effective on areas where the water diverted at any one point reaches 0.5 cubic meters/s. The next step or refinement is the conveyance dikes or ditches which transport the water from the diversion point on a natural water course to the crop growing areas. This may be some distance, up to several kilometers, in which case the dikes are actually ditches or canals. They can be built with earth taken from above or below the dike alignment. If the ground on which they are constructed has little slope, a strip up to 150 meters wide above the dike will be covered with water and irrigated whenever the system is in operation.

Spreading dikes are often found at the end of a conveyance dike. These dikes are usually a continuation of the conveyance dike with outlets for water. At appropriate intervals, part of the water is turned onto the land below the dike by means of outlets through the dike. For fairly clear water, outlets should be at the bottom of the flow channel at an elevation as the land on the lower side, thereby reducing erosion.

Waterspreading systems need a careful design and engineering layout to withstand floodwaters. While potential sites are found on many arid and semiarid ranges, they must be selected with full consideration for topography, soil type, and vegetation.

Desert strip farming

In arid and semiarid regions, although only a very small percentage of the rainfall reaches major stream channels, considerable runoff occurs on the gently sloping upland watershed areas. Desert strip farming makes use of this water by employing a series of terraces that shed water onto a neighboring strip of productive soil. They are often tiered up a hillslope, but on level terrain, an artificial slope for the catchment can be made by mounding the soil between the strips. The watershed section can be left in a natural state, cleared of vegetation, planted with range grasses or treated by some water-harvesting technique to induce runoff. (Figures 8 and 9)

Improvement and Maintenance

The discussion that follows pertains mainly to the operation, improvement, and maintenance of waterspreading systems for forage production. The principles, however, are similar for using this method on other crops and for other methods of runoff agriculture.

Common design defects

It is difficult to design a waterspreading system which is free of flaws when first constructed. The flow of water is seldom the same in any two storms. Nevertheless, the system must handle these variable flows by one automatic plan. Incomplete and inaccurate basic data are frequently a further handicap.

Usually the first flow of water through the system will reveal the flaws in design. If the designer can be on hand to watch the water flow through the system, he will be able to recognize the defects of his plan much more quickly than if he has to study the effects of the flow after it has passed by. Following are some of the effects that may appear after the system receives a flow of water:

1. Too great a concentration of water hitting certain sections of a dike with too high velocity. This may cause the water to overtop the dike or to break through. The solution of this problem may require the relocation or widening of a spillway from the dike above. The difficulty might be solved by a diversion dike or ditch above to increase the spread of the water. Possibly the dike may have to be raised in height or reinforced.

2. Dry areas not receiving water. Often a short ditch leading water to the dry spot will solve the problem, or a dike may be required to divert water to the dry area. A pipe may have to be put through a dike to let water come through to the dry spot. Sometimes partial dike or spillway relocation is necessary. The designer should not expect to irrigate all of the spreader area in each run. If 65 to 85 percent of the area can be given a good wetting in the average water run, a successful design has been attained.

3. Too much or too little water coming through the openings in flood spreaders. This fault can be corrected by reducing or increasing the size of the opening.

4. Too rapid concentration of flowing water in the system. This flow may require more small plugs or dikes in natural drainage ways, in old road ruts and trails, in low spots, in basin lips, in the borrow pits, etc., to turn out the water frequently and keep it in a sheet. Often in wild flooding systems, only the primary dikes are constructed at the beginning and the secondary dike construction is delayed until a flow of water has gone through the system, thus indicating where the secondary dikes will do the most good.

5. Improper division of water flowing into the borrow pit and that moving directly towards the next dike in flood spreaders. Corrections can be made with ditches or wing dikes.

Common maintenance problems

Maintenance of water-spreading systems should be given prompt and careful attention to avoid much heavier costs later. If sediment accumulation is slow, the maintenance costs usually decline to a fairly low figure after about the third year. By this time, the weak spots have been strengthened and the flaws in design have been corrected in connection with maintenance work. In addition, the dikes have settled and have in some cases become partially covered with soil-binding vegetation. On the other hand, if sediment accumulation continues to be great, there may be heavy annual maintenance work to raise the dikes and adjust dike design as needed.

In some cases, channels behind diversion dikes may have to be cleared of sediment. The elevation of the floor of the diversion may have to be raised to provide sufficient flow in channels made inadequate by sedimentation.

Very often heavy maintenance costs on a waterspreading system can be reduced by improving vegetation on the upper watershed to help prevent the runoff from coming down in one big flash flood of terrific force but short duration. Delayed runoff may save dikes from being overtopped and breached. It will also reduce the amount of sediment carried from the watershed and stream channel into the spreading system.

Some of the more common maintenance problems are as follows:

1. Gullying at the spillways. Slight gullying at the spillways is frequent and nothing to cause grave concern. If the gullies spread or entrench quickly it may be necessary to make the spillway wider by tearing down some of the dike at the spillway end in order to give the water more spread space. More openings or pipes may have to be put through the dike in order to cut down the amount of water going to the spillway.

2. Excessive widening or plugging of the spreader dike spillway. Excessive widening may occur as a result of erosion at the end of the dike. It can usually be stopped by building a riprap face on the end of the dike. Plugging is usually caused by deposits of sediment or debris which may have to be removed or smoothed out from time to time.

3. In straight channels paralleling dikes, obstructions, such as rocks, drift, shrubs, or earth projections, may deflect the current against the loose dike fill causing the dike to wash or cave. Remove such obstructions to permit free flow.

4. Gullying in the return or excess water channel. It is well to note the tail or excess water area particularly after a big flow. If head cuts are developing, direct the water to a more favorable location if possible. At least keep it in a thin sheet where it moves over areas likely to erode. It is sometimes impossible to avoid some erosion for a few years while an artificially sloped and vegetated area develops an adequate cover which will take the flow without eroding. The maintenance of the excess channel may require protection from grazing by fencing.

Note: Much of the material on water harvesting was excerpted from Cluff and Dutt, 1975 and much of the information on runoff agriculture was obtained from Fogel, 1975.

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TABLE 1

RELATIVE COST AND EFFICIENCY OF CATCHMENTS
DEVELOPED AT THE UNIVERSITY OF ARIZONA
December, 1972

Catchment Methods	Approx. Cost per Square Yard	Approx. Cost per Acre	Efficiency in Percent	Est. Life
Compacted Earth (CE)*	$0.03-0.05	$150-250	30-60	Indefinite
Compacted Earth Sodium Treated (CEST)*	$0.06-0.10	$300-500	40-70	Indefinite
Graveled Plastic (GCP)**	$0.20-0.50	$1000-2400	60-80	20-25 years
Asphalt-Plastic				
Asphalt-Chip-Coated (APAC)***				
Polyethylene Reinforced	$0.50-0.60	$2400-2900	85-95	10-15 years
Polypropylene Reinforced	$0.90-1.00	$4400-4900	85-95	10-15 years

* Prices and efficiency of CE and CEST Catchments are dependent on soil type, cost of clearing and shaping. Maintenance consists of weed removal and recompaction as needed. Additional NaCl may be required periodically prior to recompaction for maintenance of the CEST Catchment.

** The variation in price of the GP Catchment is primarily dependent on the cost of the gravel and to a lesser extent the cost of clearing and shaping. The cost of the 10 mil black polyethylene plastic to be used is relatively stable. Maintenance consists of adding gravel if necessary on exposed portions of the catchment.

*** Prices of the APAC systems are based on projection of small plots. Larger installations need to be made to firm up prices. Maintenance consists of recoating with asphalt and chips every 10-15 years.

(FROM CLUFF & DUTT, 1975)

Figure 1 (Cluff and Dutt, 1975)

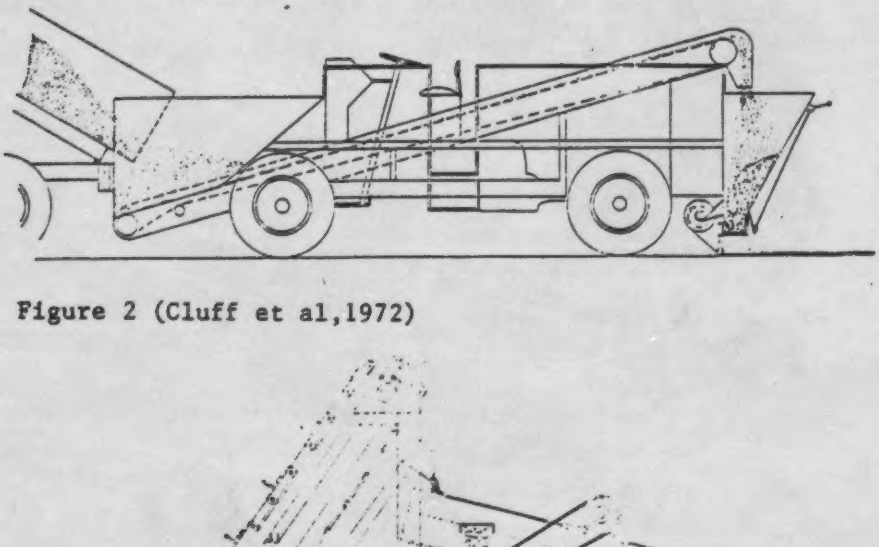
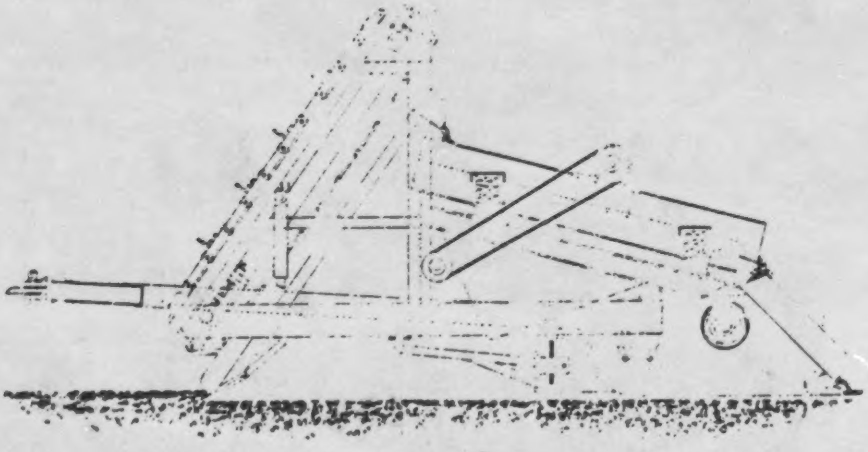


Figure 2 (Cluff et al,1972)



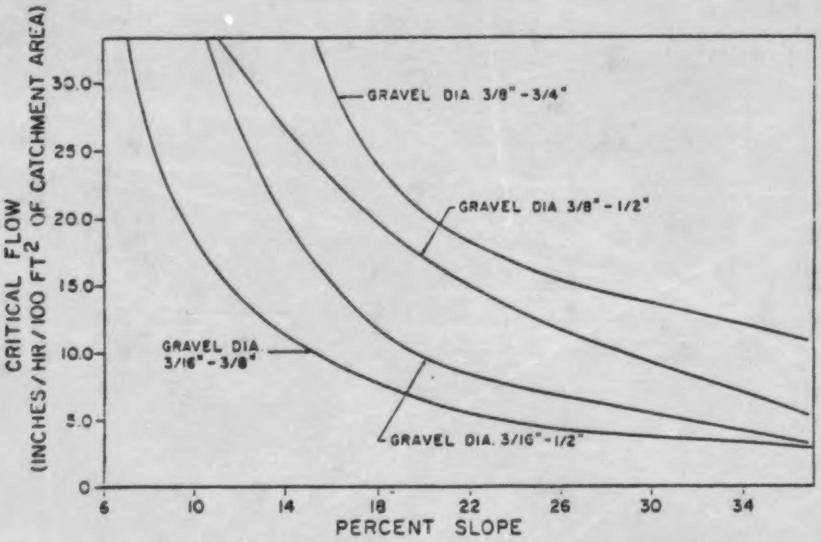


FIGURE 3. CRITICAL FLOW VERSUS SLOPE FOR SELECTED SIZE OF GRAVEL COVER. (KIRKLAND, 1969) (from Cluff & Dutt, 1975)

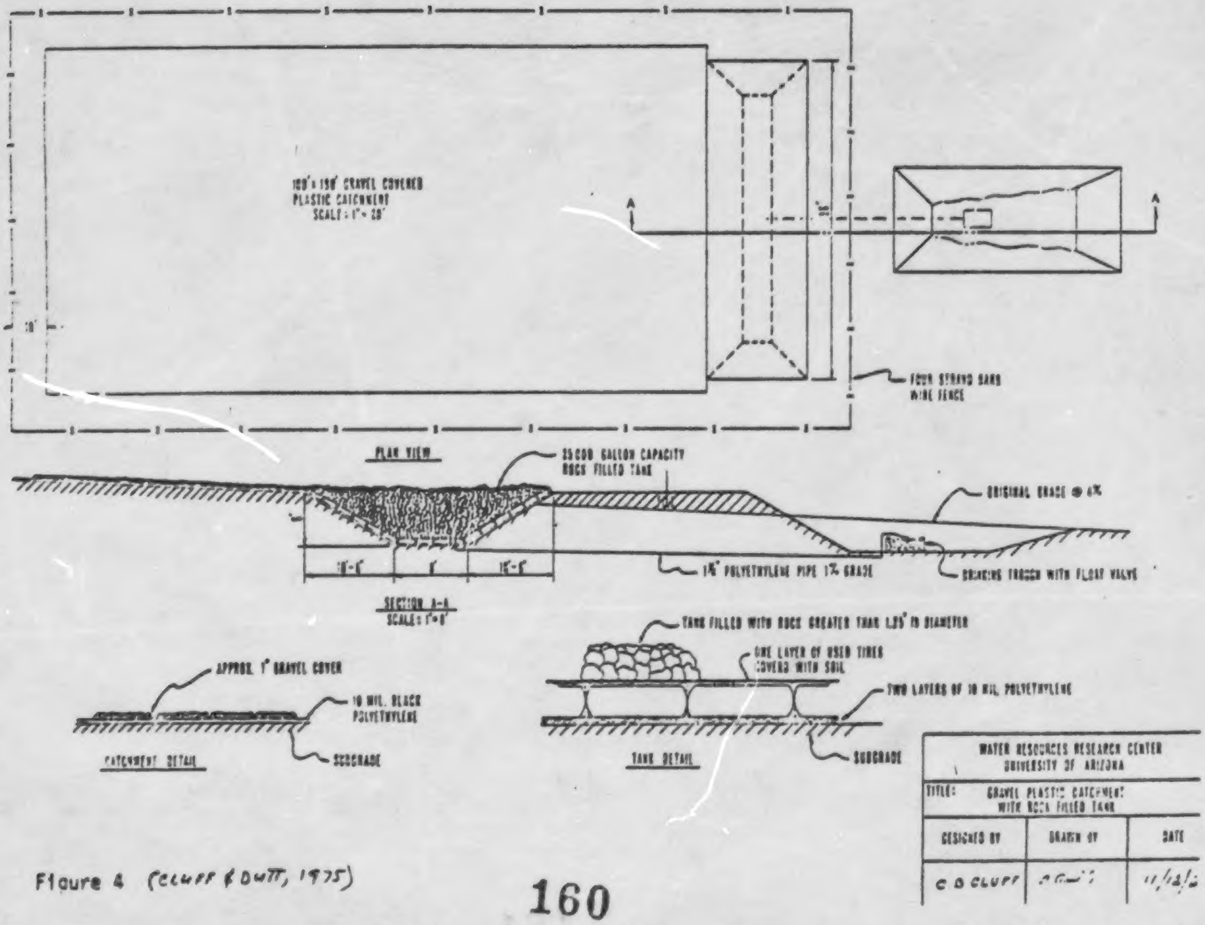

100' x 150' GRAVEL COVERED
PLASTIC CATCHMENT
SCALE: 1" = 20'
20'
36'
A
A
FOUR STRAND BARB WIRE FENCE
PLAN VIEW
25000 GALLON CAPACITY ROCK FILLED TANK
ORIGINAL GRADE @ 6%
15'-6"
8'
15'-6"
1½" POLYETHYLENE PIPE 1% GRADE
DRINKING TROUGH WITH FLOAT VALVE
SECTION A-A
SCALE: 1" = 8'
TANK FILLED WITH ROCK GREATER THAN 1.25' IN DIAMETER
ONE LAYER OF USED TIRES COVERED WITH SOIL
TWO LAYERS OF 10 MIL POLYETHYLENE
APPROX. 1" GRAVEL COVER
10 MIL. BLACK POLYETHYLENE
SUBGRADE
CATCHMENT DETAIL
TANK DETAIL
SUBGRADE
WATER RESOURCES RESEARCH CENTER
UNIVERSITY OF ARIZONA
TITLE: GRAVEL PLASTIC CATCHMENT WITH ROCK FILLED TANK
DESIGNED BY
DRAWN BY
DATE
C D CLUFF

Figure 4 (Cluff & Dutt, 1975)

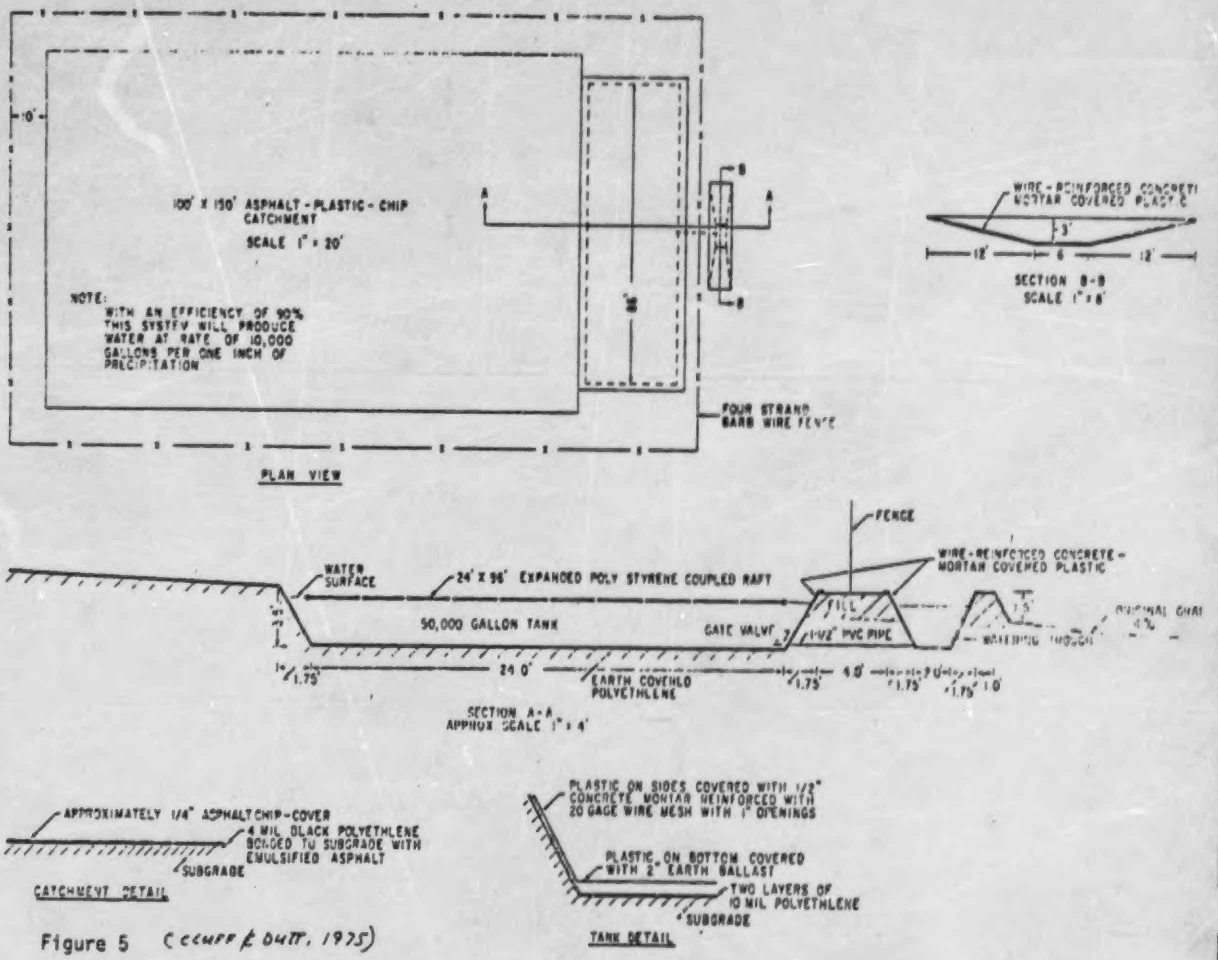

10'
100' X 150' ASPHALT - PLASTIC - CHIP CATCHMENT
SCALE 1" = 20'
NOTE:
WITH AN EFFICIENCY OF 90% THIS SYSTEM WILL PRODUCE WATER AT RATE OF 10,000 GALLONS PER ONE INCH OF PRECIPITATION
A
A
B
B
FOUR STRAND BARB WIRE FENCE
PLAN VIEW
WIRE - REINFORCED CONCRETE MORTAR COVERED PLASTIC
3'
12'
6
12'
SECTION B-B
SCALE 1" = 8'
FENCE
WATER SURFACE
24' X 96' EXPANDED POLY STYRENE COUPLED RAFT
WIRE-REINFORCED CONCRETE-MORTAR COVERED PLASTIC
FILL
1.5'
ORIGINAL GRAD 4%
50,000 GALLON TANK
GATE VALVE
1-1/2" PVC PIPE
WATERING TROUGH
1.75'
24.0'
EARTH COVERED POLYETHLENE
1.75'
4.0'
1.75'
2.0'
1.75'
1.0'
SECTION A-A
APPROX SCALE 1" = 4'
APPROXIMATELY 1/4" ASPHALT CHIP-COVER
4 MIL BLACK POLYETHLENE BONDED TO SUBGRADE WITH EMULSIFIED ASPHALT
SUBGRADE
CATCHMENT DETAIL
PLASTIC ON SIDES COVERED WITH 1/2" CONCRETE MORTAR REINFORCED WITH 20 GAGE WIRE MESH WITH 1" OPENINGS
PLASTIC ON BOTTOM COVERED WITH 2" EARTH BALLAST
TWO LAYERS OF 10 MIL POLYETHLENE
SUBGRADE
TANK DETAIL

Figure 5 (Cluff & Dutt, 1975)

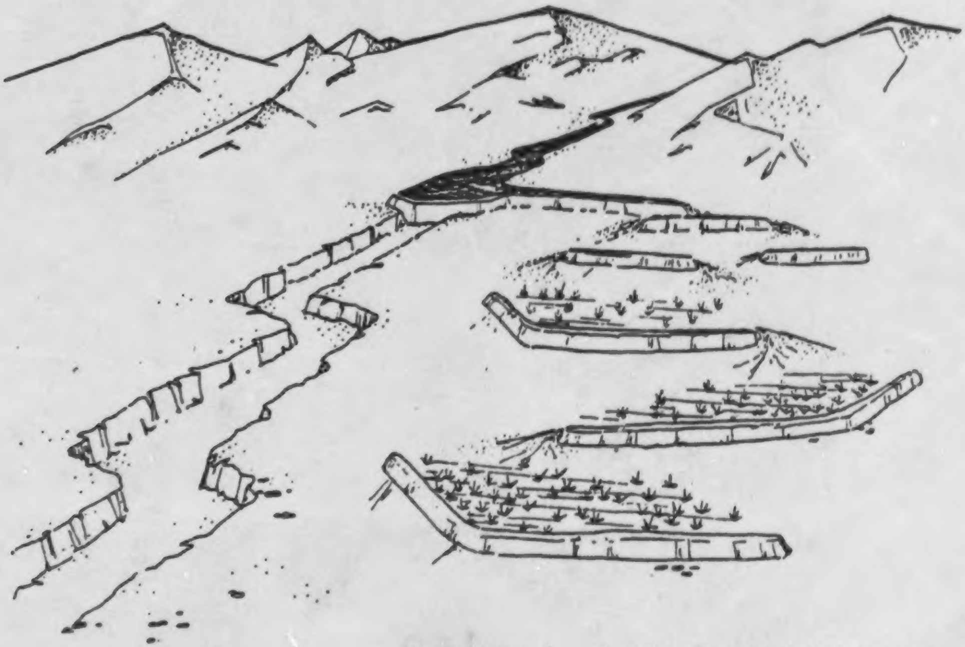


Fig. 6. Schematic of a waterspreading system.
(Fogel, 1975)

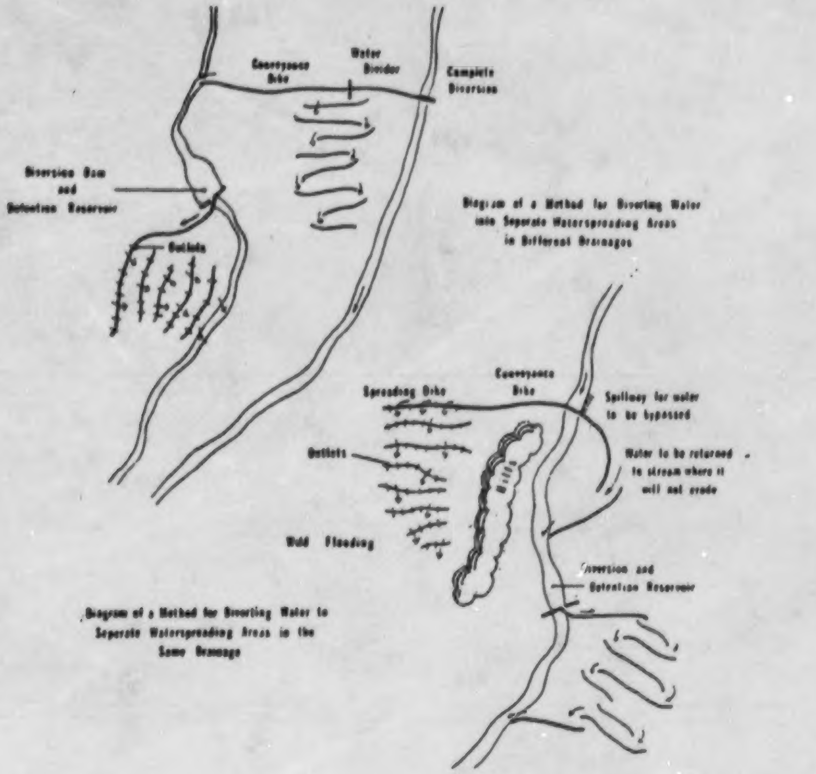

Conveyance Dike
Water Divider
Complete Diversion
Diversion Dam and Detention Reservoir
Outlets
Diagram of a Method for Diverting Water into Separate Waterspreading Areas in Different Drainages
Spreading Dike
Conveyance Dike
Spillway for water to be bypassed
Water to be returned to stream where it will not erode
Outlets
Wild Flooding
Diversion and Detention Reservoir
Diagram of a Method for Diverting Water to Separate Waterspreading Areas in the Same Drainage

Fig. 7 Possibilities for various types of structures used in waterspreading systems are illustrated. (Fogel, 1975)

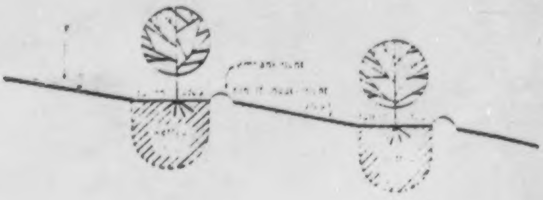


FIGURE 44. Profile of runoff-irrigated orchard (schematic)

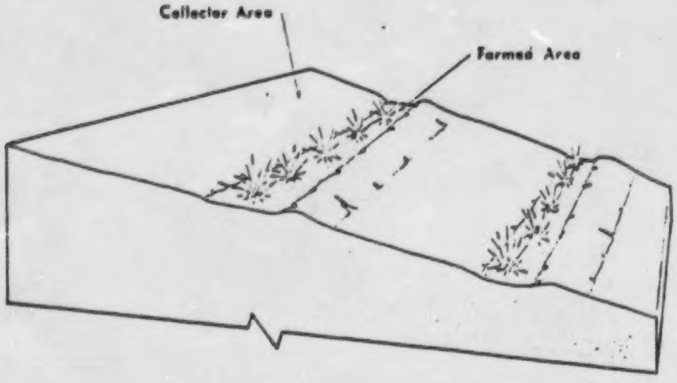

Collector Area
Farmed Area

Fig. 8 ARTIST'S CONCEPT OF DESERT STRIP FARMING (Fogel, 1975)

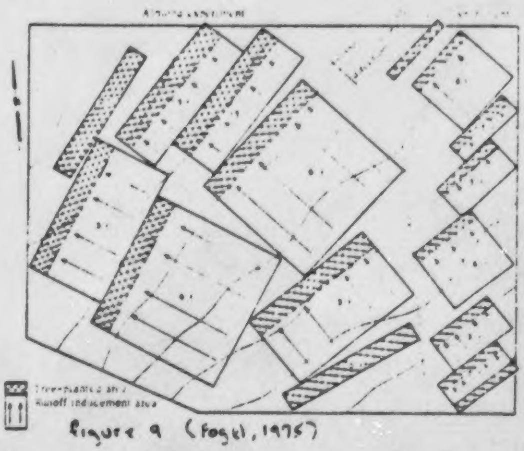

Tree-planted area
Runoff inducement area

Figure 9 (Fogel, 1975)

Water Yield Improvement

Introduction

Demands for surface and ground water in much of the world require that all potential sources of water be evaluated for possible development. To this end, several approaches to water augmentation and methods for better water management have been explored. Water harvesting, reuse, salvage (by removal of riparian plant communities), and vegetation management on upstream catchments are some of these approaches.

Of specific interest here is the management of vegetation on upstream catchments to increase the yield of usable water. It appears that water yield can be increased through vegetative treatments that benefit, or are at least compatible with, other natural resource objectives. To furnish an assessment of these possibilities, underlying concepts of vegetation management for water yield improvement will be presented, along with a brief summary of several worldwide studies on the effects of altering vegetative cover on water yield.

Vegetation Management for Water Yield — Concepts

Many studies conducted throughout the world have demonstrated that annual water yields can be increased following the implementation of vegetation management practices. In general, the increased runoff is often attributed to decreased evapotranspiration on the watersheds. That is, following treatment, less precipitation input is converted to vapor as a result of rainfall and snowfall interception and transpiration, and more is made available for streamflow runoff. Presumably, the reduced evapotranspiration is due to changes in the structure and composition of vegetation on the watershed.

Evaporation processes generally account for a significant proportion of the annual precipitation input on most watersheds. Consequently, the potential to increase water yield by decreasing evapotranspiration is attractive. For example, 85 to 95 percent of the annual precipitation is evaporated or used by plants on many watersheds in arid and semiarid regions, leaving only 5 to 15 percent available for streamflow runoff. On high elevation mountain watersheds in the snow zones of the world, the annual water yield may be as high as 50 percent of the precipitation input, but the evapotranspiration component is still significant and potentially subject to reduction through vegetation management.

Perhaps the above concepts may best be illustrated with a hypothetical but realistic water budget for a forested watershed (Table 1). Prior to treatment, average annual precipitation and evapotranspiration were 635 and 560 millimeters (mm), respectively, leaving 75 mm for streamflow runoff. After the implementation of a vegetation management practice, perhaps a partial harvesting of the forest overstory in a timber management operation, the annual streamflow runoff is increased by 25 mm (from 75 to 100 mm) due to a reduction in evapotranspiration of 25 mm (from 560 to 535 mm). The annual precipitation input of 635 mm remained the same, as basic precipitation patterns are usually not affected by modifications in the structure and composition of vegetation cover.

In the case illustrated, annual water yield increased by 33 percent, while annual evapotranspiration decreased by 5 percent. It should be noted that, no matter what vegetation management practice is imposed on watersheds, the annual evapotranspiration may only change but little. However, as demonstrated above, even a small reduction in evapotranspiration may cause significantly increased streamflow runoff.

Indications are that, for appropriate conditions and situations, water yields can be augmented by vegetation management practices without denuding watersheds of plant cover and without unacceptable changes in erosion and sedimentation. Evidence also suggests that vegetation management designed for water yield improvement can be developed to be compatible with other natural resource uses and values, and in some cases even to be complementary.

If the structure and composition of vegetation at the interface of earth and atmosphere can be modified by management practices, evapotranspiration may be reduced with the result that more of the annual precipitation input will be released from watersheds as usable water. This concept is the primary basis for the belief that vegetation can be managed for water yield improvement as well as for other natural resource products and amenities.

Summary of Water Yield Improvement Experiments

Experimental catchments, often supplemented by plot studies and computer modeling, have been used on numerous occasions to demonstrate that the hydrologic relationships of a river basin may be significantly affected by the implementation of a vegetation management practice on upstream catchments. These management practices, often imposed as a water yield improvement practice, include various types of forest cutting or removal, or changes of forest cover from one tree type to another, or more drastic changes in which a forest cover is replaced by another type of vegetation.

As an overview of the potentials for water yield improvement through vegetation management, a brief summary of several worldwide studies on the effects of altering vegetative cover on water yield, and the significance of the resulting conclusions, follow.

Emmenthal Mountains

In 1900, an early study of the effects of forest treatments on water yield was carried out in the Emmenthal Mountains of Switzerland. Here, measurements of climate, precipitation, and streamflow were made on two small catchments, one forested and the other pastureland, to determine the influence of forests on water production. Despite attention to detail, there was no way to ascertain that the observed differences in streamflow between the two catchments were caused only by differences in vegetation cover.

Wagon Wheel Gap

A second attempt to quantitatively analyze the influence of forests on water yield was made in the Wagon Wheel Gap investigation of 1911. The control watershed approach (in which streamflow from two similar catchments are compared during a period of "calibration," and then treating one catchment while leaving the other untreated as a control) was first used in this study of two forested catchments in the Colorado Rockies of the western United States. After eight years of calibration, one of the catchments was denuded by removing the scrub aspen and coniferous vegetation. Then, for seven additional years, streamflow from the denuded areas was compared with flow from the control catchment. This investigation conclusively demonstrated that clearing forest cover did increase streamflow. This study also demonstrated that changes in water yield could be quantitatively assessed.

Coweeta Hydrologic Laboratory

In 1934, the Coweeta Hydrologic Laboratory was established by the USDA Forest Service to analyze the effects of various forest cutting and vegetative conversion treatments on water yield in the humid mountains of the eastern United States. Mixed hardwoods with basal area densities of 20–25 square meters per hectare characterized the original forest conditions on the twelve experimental catchments at Coweeta. Treatments implemented and then evaluated included clearcutting with and without control of regrowth, poisoning of forest overstories on portions of catchments with regrowth restricted, and thinning above and below by selective logging.

With the exception of limited thinning (25 percent of the basal area removed), the treatments evaluated increased water yield by varying amounts. In general, these increases were greatest immediately after treatment, and the duration of effect was dependent, in part, upon the severity of treatment. One of the catchment studies is the site of the only cutting experiment replicated in time.

Kamabuti

Coniferous and deciduous forest overstories on a small mountainous catchment in Kamabuti, Japan were cleared in 1948, with subsequent annual recutting on sprouts. Significant water yield increases were observed following treatment, although these increases were restricted to the growing season.

Fernow Experimental Forest

In 1951, the USDA Forest Service began gauging on several small catchments at the Fernow Experimental Forest in the Allegheny Mountains of West Virginia in the eastern United States. Original forest conditions on these catchments were mixed hardwoods at 20-25 square meters of basal area per hectare. After calibration, water yield improvement studies were designed and implemented to determine effects of logging on streamflow. Treatments evaluated consisted, for the most part, of thinning by alternative silvicultural practices.

As was found at Coweeta, with the exception of limited thinning (in this case, approximately 15 percent of the basal area removed), the treatments evaluated increased water yield by varying amounts. Also, these increases were greatest immediately after treatment.

Fraser Experimental Forest

To assess effects of forest cutting on snow pack dynamics and subsequent streamflow, the USDA Forest Service logged mature lodgepole pine and spruce-fir in strips and blocks on an experimental catchment in the Colorado Rockies of the western United States. As a result of this treatment, in which about 40 percent of the catchment was clearcut from 1954 to 1956, streamflow increased during the snowmelt period (essentially May and June). This increase in water yield was attributed, primarily, to redistributions in snowpacks brought about by a restructuring of the forest overstories.

Kimakia

In 1956, the high montane and bamboo forests on an experimental catchment at Kimakia in Kenya, East Africa, was cleared and planted to patula pine. Vegetables were grown among the pines until the third post-treatment year (when the pines were 3 to 5 meters high). A large increase in water yield was observed following cutting, with the greatest increases immediately after treatment. No change in seasonal patterns of streamflow occurred.

San Dimas Experimental Forest

At San Dimas, located in the semiarid region of California in the western United States, the USDA Forest Service selectively treated chaparral vegetation thought to use proportionally large quantities of water. In 1958-59, riparian vegetation was cut and regrowth controlled on one experimental catchment (less than 2 percent of the area treated), while chaparral on moist sites with deep soils was sprayed with herbicides on another catchment (about 40 percent of the area treated). Both treatments increased water yield, with dry-season streamflow affected more significantly.

A disastrous wildfire swept San Dimas in 1960, destroying all existing vegetation. Dry-season streamflow increased appreciably following the wildfire on the two catchments treated, while streamflow from untreated (control) but burned catchments did not.

H. J. Andrews Experimental Forest

To determine how logging activities affect streamflow on the western slope of the Cascade Range in Oregon, United States, two experimental catchments were subjected to staged treatments (road construction, cutting of the coniferous overstories, and burning) during the period of 1959 to 1963. Significant increases in water yield occurred in the low flow season after each treatment, but they were small in actual volume (less than 0.1 mm per day).

Jonkershoek Forest Reserve

Analysis of streamflow from an experimental catchment on the Jankershoek Forest Reserve, South Africa, has shown a 50 percent increase in water yield after one-third of the radiata pine forest cover was removed 16 years following planting. Presumably, most of the increase in flow was due to less transpiration losses. This effect of increased streamflow was maintained for three years after the thinning treatment.

Junquillar Basin

To evaluate effects 6 established land use patterns on the western slope of Chile's coastal mountains, three experimental catchments (two burned and an unburned control) were gauged in the Junquillar Basin during 1970. Native vegetation on the area included small trees (roble maulino, white boldo, and litre), shrubs, and a few grasses. Radiata pine had been planted on the burned catchments, a common practice in the region.

While still exploratory, preliminary results have indicated that streamflow from the catchments did not differ noticeably. However, peak flows, which are more sensitive to treatment and may be more important in a region of high rainfall, were higher on the burned areas.

North Maroondah

Measurements of effects of thinning radiata pine plantations and regrowth mountain ash on streamflow volumes are the subject of major experimental catchment studies conducted by the Melbourne and Metropolitan Board of Works in the North Maroondah area of Australia. Preliminary results suggest that forest manipulations involving thinning of these forest cover types may be a feasible approach to increasing Melbourne's water supplies.

Arizona Watershed Program

Watershed managers in the southwestern United States, a semiarid region with short water supplies, have been particularly interested in evaluating possibilities of water yield improvement by vegetation management. As a result, the Arizona Watershed Program (involving federal, state, and private interests) was formulated to study the influence of vegetation management practices on the hydrologic processes affecting water yield improvement. While many vegetation types have been investigated, results of experimental catchment studies to date indicate that the greatest opportunities for water yield improvement by vegetation management are found in chaparral shrub communities, pinyon-juniper woodlands, ponderosa pine forests, and mixed conifer (including aspen) forests.

It appears that water yield from chaparral shrub communities can be increased by removing shrub overstories and establishing a cover of grasses and forbs. Although experimental catchments have been established by the USDA Forest Service at several locations in chaparral, only the Three Bar Watersheds, located in east-central Arizona, will be considered here.

In 1956, four small catchments (B, C, D, and F) were established on Three Bar. All were burned over by wildfire three years later. With the exception of Catchment C, all of the catchments were seeded with grass shortly after the fire; Catchment B was reseeded and Catchment C seeded for the first time in 1960. After calibration, control of chaparral shrub regrowth with herbicides was attempted on Catchments C and B and changes in water yield were observed. On Catchment C, the shrubs were controlled through aerial applications and hand treatments with herbicides. Annual water yield following treatment increased over 325 percent. Hand application of herbicides to the shrubs on the north-facing slopes, comprising 40 percent of Catchment B, increased annual water yield by 320 percent. Complete conversion on Catchment F resulted in an annual water yield increase of approximately 700 percent.

Originally thought to have potential, improving water yield by manipulating pinyon-juniper woodlands does not appear promising at this time. On Beaver Creek and Corduroy Creek, experimental catchments located in north-central and east-central Arizona, respectively, removal of pinyon-juniper overstories by mechanical techniques (chaining, cabling, and hand clearing) has not increased water yield. However, water yield was improved on one experimental catchment by killing pinyon and juniper trees with herbicides and leaving them stand. The increase on Beaver Creek Catchment 3 after aerial spraying of herbicides was 65 percent annually. However, this study was too limited to make general statements about chemical conversion treatments for increasing water yield.

Opportunities for and estimates of water yield improvemnt through vegetation management in ponderosa pine forests are synthesized from the results of experiments on Castle Creek, located in east-central Arizona, and Beaver Creek. For purposes of discussion, vegetation management options in ponderosa pine forests may be placed into two categories: clearing of forest overstories and thinning of forest overstories. Various alternatives are possible within these categories, however. For instance, clearings can be arranged and oriented in various patterns, and intensity of thinning can be varied.

Clearing of ponderosa pine from one-sixth of the West Fork of Castle Creek and thinning the remaining five-sixths increased annual water yield by over 25 percent. On Beaver Creek Catchment 12, an increase of approximately 30 percent has occurred annually since the complete clearing of the forest overstory. Clearing forest overstories from 20 meter side strips and leaving alternating uncut strips 60 meters wide increased annual water yield by nearly 15 percent on Beaver Creek Catchment 9. Thinning the forest overstory by group selection on Beaver Creek Catchment 17 increased annual water yield by about 20 percent.

Estimates of water yield improvement through the manipulation of mixed conifer forest overstories are based, in part, upon partial conversion experiments on the Workman Creek Water in east-central Arizona. On the North Fork of Workman Creek, deciduous riparian vegetation was removed, and two-thirds of the moist-site and dry-site forests were converted to grass. The resulting increase in water yield was approximately 85 percent. On the South Fork of Workman Creek, annual water yield increased nearly 115 percent after an individual tree selection cut was followed by a conversion cut.

Discussion of Water Yield Improvement Experiments

A review of worldwide studies of the effects of altering vegetative cover on water yield suggests that several generalizations can be made:

1. reduction in densities of forest overstories increase water yield:
2. establishment of forest overstories on sparsely vegetated land decreases water yield; and
3. response of water yield to treatment is highly variable and, for the most part, unpredictable.

The above generalizations must be qualified when specific experiments are considered but, in most instances, they are accurate. With few exceptions, the worldwide studies have shown a definite response to vegetative cover alteration. However, the magnitude of treatment response has varied considerably. For example, removal of scrub aspen and coniferous vegetation in the Colorado Rockies of the western United States caused streamflow to increase only 35 mm during the first year after treatment, while complete cutting and removal of high montane and bamboo forests in the mountains of East Africa increased water yield in excess of 450 mm during the first year. These extremes reflect the diverse nature of the results and suggest the complexity of the causative factors.

To summarize, the results of experimental catchment studies suggest that vegetation management may have potential for increasing water yield on many drainages throughout the world. Furthermore, if desired, many of these management practices can be designed to maintain or enhance the production and use of associated natural resources, including timber, domestic livestock, wildlife, aesthetics, and soils. Such possibilities are not surprising, as many of the vegetation management practices tested in various parts of the world are employed to benefit other natural resources. Therefore, it seems possible that vegetation management can satisfy increasing demands for other natural resources while it is increasing water yield.

It must be emphasized, however, that the results presented in this overview are based, for the most part, on research tests and not operational programs. Hopefully, these research findings can be coupled with economic and social considerations to develop operational practices that will

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Water Quality on Upland Watersheds

Dissolved Chemical Consituents

The hydrologic cycle depicts the movement of water through a forest ecosystem. Water flow is a major component of the environment, linking together the atmosphere, soil, biotic, and stream compartments of the system. Since water is the carrier of materials and energy between the atmospheric and terrestrial portion of the system and the stream, an understanding of the processes which affect water quality in forest streams has as its basis an understanding of the hydrologic process.

To understand various impacts, one must realize that forest streams are not separate and distinct from the area they drain, but are an intregal part of the ecosystem. As water comes into contact with each part ot the system, the chemical characteristics adjust accordingly. Chemical reactions and physical processes occur as the water contacts the atmosphere, soil and biota. It is these processes and the condition of each compartment that determine the amount and kind of chemical species in solution.

The major sources of dissolved constituents in water draining upland watersheds are: geologic weathering of parent rock; meteorological inputs; and biological inputs. Chemical and physical weathering converts rock minerals into soluble or transportable form. Dissolved matter, including organic compounds and mineral ions, are added to the forest ecosystem in precipitation, dust, and other aerosols. The biological inputs are mainly materials gathered elsewhere and deposited in the forest by animals, including man, and also the photosynthetic production of organic material from inorganic substances followed by the subsequent breakdown of the organic back to the inorganic compounds.

In undisturbed ecosystems, the rock substrate and soil generally control the relative concentrations of metallic ions (cations such as Ca^+ , Mg^{++}, K^+, and Na^+), while the relationship of biological and biochemical processes in the soil to precipitation rarely governs the anionic ($HCO3^-$, $NO3^-$, and $PO4^=$) yield. Anions, such as chloride (Cl^-), nitrate ($NO3^-$), and sulfate ($SO4^=$), at least in the absence of abundant sulfide minerals, originate from the atmosphere; the output of these ions is regulated by soil processes.

. Although appreciable quantities of nitrogen, sulfur and other elements are often found in precipitation and in dust and dry fallout between rains, the soil under natural forest conditions is considered the greatest contributor of dissolved elements to runoff. Other components of the ecosystem (biologic, atmospheric, rock substrate), through their influence on soil processes and properties, play an important role in determining the chemistry of outflow.

Such dissolved compounds can leave a system by water transport over and through the soil or forest floor to either groundwater or surface flow.

The above processes are often lumped under the term nutrient cycling, which consists of inputs, outputs, and the movement of dissolved solids within the system. This is chiefly concerned with outputs, that is, the streamflow from upland basins and the various factors influencing the chemical components in this runoff.

The movement of water through the soil, along with biological activity controls the ionic composition of water leaving upland watersheds as streamflow. The most chemically active components of a forest soil are the clay and organic colloids. Soil colloids have a large capacity to exchange ions in solution for those absorbed on their surfaces. Clays have high exchange capacities compared with most other minerals because of their large surface area per unit volume and their negative electrical charge.

A simplified picture of the exchange process would be that cations absorbed on soil colloids are selectively exchanged for hydrogen ions from the soil water. The hydrogen ions come principally from the solution of carbon dioxide in water and dissociation of the resulting H2CO3 molecule into a hydrogen ion and a bicarbonate ion. The dissolved carbon dioxide originates chiefly in the metabolism of microorganisms and plant roots in the soil. Based on the above assumptions, only the water remaining for some time in interstices between soil particles is likely to pick up an appreciable load of dissolved carbon dioxide and consequently be effective in leaching mineral ions.

Studies have shown that the ionic concentrations and their relationships to discharge are quite variable. For example, a direct relationship exists between H^+, $NO2^-$ concentrations and discharge, but no relationship between discharge and the concentrations of Mg^{++}, Ca^{++}, $SO4^=$, and K^+ has been found in streams on an experimental forest in New Hampshire. Elsewhere, individual cation concentration, when considered throughout the year, appeared to be independent of discharge rate on four experimental watersheds in the southern Appalachians. An inverse relationship to cation concentrations and discharge of selected streams has been reported in Colorado. Also, an inverse relationship between ion concentrations and discharge was observed from a stream in California. In large streams, general ionic concentrations are commonly lower at times of high flow than at low flow due to the long residence time of water in the soil during the dry weather, which gives more opportunity for chemical reactions.

Concentrations at a given flow rate are often greater when a stream is falling than when it is rising. This phenomenon might be explained by noting that during periods of rising hydrograph following rain or rapid snowmelt, most water movement occurs as subsurface flow. Also, some water enters root channels, worm holes, and other crevices and flows through these openings without coming into direct contact with the soil's chemically active compartment. On the falling hydrograph, moisture is confined to soil pores for longer periods, where it comes into intimate contact with active colloids.

It is thought that thin films of water moving slowly through unsaturated soil make a major contribution to base flow of streams during dry periods. This unsaturated flow is particularly important in forest drainage basins that are relatively steep with deep soil profiles.

Just how the mechanism of mass flow works through unsaturated soil is still not completely known, but active water films are in close contact with soil particles for long periods. It might be well to point out that more research is needed in the area of the removal and transport mechanisms of ions in unsaturated flow and the role of this flow in determining the ionic composition of streams draining forested lands.

With respect to the mechanisms of ion transport involved during short periods of rapid flux, such as those associated with a wetting front through a forest soil, it has been hypothesized that one probable factor controlling cation leaching in a mineral forest soil is the anion level of the soil solution. As previously mentioned, the soil has a large component of immobile negative charges in the form of the exchange complex, and cation mobility is dependent on the production of a mobile anion. The bicarbonate ion, which comprises a large portion of the total anions present in the soil solution, is formed from carbon dioxide dissolved in percolating water. Microbial action in the forest floor is the primary source of such carbon dioxide. It is proposed that hydrogen ions associated with the bicarbonate ions replace exchangeable cations from the soil complex. These cations are transported along with mobile bicarbonate ions during periods of soil water flow.

Land management practices can significantly influence ionic balances. For example, if the cation-anion balance of the soil solution is changed temporarily by the addition or subtraction of an ionic species due to logging or fire, the equilibrium is restored by an equivalent change in the concentrations of oppositely charged ions. This will be considered in more detail later.

Once water has reached an effluent stream, it is often considered to consist of a base flow fraction made up of ground water that infiltrates into the channel and a direct runoff fraction, which in turn enters the drainage system during and soon after precipitation periods. The direct runoff presumably has no residence time in the ground water reservoir and only a short contact with soil or vegetation. As mentioned earlier, reactions in the soil zone are commonly extensive enough that the direct runoff has a considerably higher dissolved-solids content than the original rain or snow. Usually the base flow, when present, has a still greater dissolved load. Based on the assumptions outlined above, the solute concentration of river water would be inversely related to flow rate. This would not necessarily be the case if the stream were influent with base flow nonexistent.

Other natural factors in the stream itself that influence ionic composition include: reactions of water with mineral solids in the streambed and in suspension, reactions among solutes, losses by evaporation and by transpiration from plants growing in and near the stream, and effects of organic matter and aquatic organisms. This latter set of natural factors results in fluctuations of composition that bear little relation to discharge rates.

Chemical equilibria probably control a few properties of water in flowing streams. For example, the ion-exchange reactions of solutes with suspended sediment probably are rapid enough that they usually are at equilibrium. Certain oxidations, such as ferrous to ferric ion, also normally reach equilibrium. For biological processes such as the utilization and production of carbon dioxide and oxygen, the equilibrium approach is not necessarily appropriate. If the stream is to be considered a dynamic system, which it is, kinetics would better describe its chemistry rather than using a steady-state equilibrium approach. For example, the processes whereby biological organisms consume organic loads of the stream can often be better studied and understood by applying rates of reactions and processes.

When a forest is harvested (especially clearcut), trees no longer take up nutrients, and the nonmerchantable parts of trees increase forest litter. The removal of the forest canopy changes the microclimate, making it warmer and reducing evapotranspiration, the latter resulting in an increased soil water content. This increased temperature and water content of the soil accelerates the activity of microorganisms that break down organic matter. The greatly increased respiration of these organisms raises the carbn dioxide partial pressure of the soil atmosphere, which in turn increases the bicarbonate anion level and leaching loss of cations from the system.

Nitrogen losses as nitrate may also occur, when it is produced by the oxidation of organic matter (nitrification) and not utilized by the forest vegetation which has been removed.

Recent studies throughout the United States do show that following clearcutting, there is an increased loss of nutrients (cations and nitrate) from the logged area along with an increased runoff volume. This increased ionic loss along with increased runoff would possibly tend to give concentrations of ions a less noticeable increase, but total losses should be quite outstanding.

Studies have also shown that slash burning following logging produces an even greater increase in the release of ions from the forest floor litter and mineral soil. This increase in the release of ions is due to the breakdown of the organic debris to a soluble form, making it easily removed from the soil by leaching water. Generally, this process can lead to an increase in the total loss of nutrients in streamflow. However, the above may not always happen. For example, a moderately severe fire in a conifer stand had no specific effect on the concentrations of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, or $HO3^{-}$ in the stream. It was postulated in this study that ash constituents were dissolved by light rainfall and latched into the permeable forest soil before the first snow. Because of the acidic nature of the soil, the dissolved cations were absorbed on the exchange complex instead of being washed directly into the stream. Of course, rains of high intensity following a severe fire could move large quantities of soluble ash compound into flowing streams.

As the forest regenerates following a perturbation, the dissolved load of the stream also returns to levels experienced before the disturbance.

In summary, the dissolved load of streams after various forest activities, such as clearcutting or burning, is a function of the several soil, vegetation, and climatic characteristics that describe a forest ecosystem. Soil characteristics, such as porosity and texture, determine the pathway and rate of water movement in or over soil, soil erodibility, and how strongly nutrients will be held within the soil matrix. Vegetation characteristics, such as species composition, influence the rate of nutrient uptake. The rate of revegetation controls the rapidity with which recycling begins after system disruption. The leaching rate is influenced by form, chemistry, amount and intensity of precipitation. Generalization of effects of forest management in widely differing upland ecosystems is precluded by the intricate interaction amoung these many variables.

Suspended Sediment

Undisturbed upland watersheds generally have low suspended sediment concentrations (10 to 20 ppm mean concentration). Higher concentrations are usually the result of a perturbation to the drainage area such as roads, logging or natural catastrophes which can cause accelerated erosion.

Erosion of soils produces sediment in waters draining forest lands. Three major erosion processes are of concern: surface erosion, mass soil movement and channel erosion.

Surface erosion is the direct result of rain striking unprotected soil surfaces. Soil particles are detached and transported by overland flow across the soil surface. This process is relatively non-existent in the non-disturbed, well protected forest floor which has a high infiltration rate. Accelerated erosion can be expected in cases where the protective forest floor litter has been removed exposing mineral soil along with soil compaction.

Mass soil movement is the process by which large volumes of soil and rock materials move downslope under the influence of gravity. This movement is usually prevalent in areas where the geologic substrate is naturally unstable.

Channel erosion is the result of abrasion by water or debris on the stream bank and bed. This erosion process can contribute heavily to suspended sediment. It has been found, for instance, that 25 percent of the sediment yields in the Willamette River in western Oregon could be attributed to logging activity, 25 percent to agricutlure, and 50 percent to bank cutting in the main river.

In general, increased velocity of streamflow will give an increased concentration of suspended sediment. Also, any practice that reduces the stability of the streambank or other watershed surfaces will cause suspended sediment to increase.

Roads and road building are considered to be the principle sources of suspended sediment. Studies and observations have shown that as much as 90 percent of the sediment produced from timber sale areas in the northern regions of the United States comes from roads.

There have been numerous studies relating forestry activities to accelerated erosion and sedimentation. Generally,it has been found that in most cases, watershed damage from felling, limbing and bucking of trees during timber harvesting is probably negligible.

Skidding and yarding activities can cause accelerated erosion, however, but the great variety of techniques and machines used in this operation provide alternatives for minimizing damage on many sites. A major rule here is, the less compactive and disturbing the contact with the forest floor the less will watershed damage result from skidding and yarding.

Balloon logging probably results in the least compaction and disturbance because the logs are transported free in the air over most of the cut area. Grapple and yarding systems are intermediate between skyline and high lead, as they combine features of each. The most destructive technique of all is tractor logging.

Harvest areas on upland watersheds are subject to erosion until new vegetative cover is established, since it is the exposed mineral soil that is a major source of suspended sediment. Furthermore, varying degrees of damage to the forest floor result from the several combinations of harvesting and log transport systems.

Clearcutting and removal of trees by the balloon system resulted in the lowest soil sediment deposited in streams and also had the smallest exposure of bare soil. Clearcutting by tractor, as expected, exposed the most mineral soil (over 29 percent).

Once an area is logged, slash is frequently eliminated by controlled burning. Intense fires often lead to accelerated erosion. Extremely hot fires consume vegetation, litter and duff materials and leave the soil unprotected. Such fires may also reduce the organic content of the soil and alter the stability of surface soil aggregates. Infiltration rates are often reduced and surface runoff can be increased by the production of a non-wettable surface layer.

Controlled burns are usually not intense enough to cause erosion problems.

Fire can also be a contributor to accelerated mass wasting. This is due largely to the destruction of the natural mechanical supports of soils. In northern Utah, logging and burning produced increases in mass soil movements due to the loss of mechanical support of the root systems of trees and plants. Many other studies support the relationship of fire, logging and road building to accelerated mass movements and resulting stream sedimentation.

Bacteriological Quality

Quite often, bacteriological indicators are employed to gain knowledge of the biological quality of streamflow. An estimate of these organisms is a relatively simple, fast and inexpensive index of pollution, especially when the membrane filter technique is used. Knowledge of cycles and variability of bacteria in natural waters and the relationships of bacteria to physical environmental factors is sparse.

There have been some studies of relatively undisturbed watersheds describing bacteria-environment relationships.

Seasonal coliform trends have been studied and evidence for relationships between coliform counts and certain physical environmental factors (streamflow and air temperature) has been found. Great increases in logging and stream turbidity over a period of years did not affect coliform densities, but it should be noted that the logging was on municipal watersheds and disturbance was probably minimal.

An assessment of the causes of variation in bacterial numbers of a small, unpolluted stream in Colorado indicated that the most important cause of bacteria population fluctuations was summer rainstorms of short duration, producing overland flow. When streamflow is stable during periods of no precipitation, bacterial numbers can be related to the size of the water-streambed contact surface. As streamflow increases after precipitation, bacteria are deposited in the ground water associated with the stream and are later released into the stream as it recedes. Bacterial numbers fluctuate during the winter even when temperatures are as low os 0° - 5.5°C. It has also been found that when cattle graze in marshy areas adjacent to the stream, the bacterial density of the stream rises. The bacteria counted were coliform and total bacteria.

In a measurement of bacterial groups in streamflow from mountain watersheds in Colorado, total coliform, fecal streptococcus and fecal coliform bacterial groups were closely related to the physical parameters of the stream, and they were especially dependent on the "flushing effect" of runoff from snowmelt and rain, summer storms, or irrigation. The seasonal trend for all bacterial groups was similar: low counts prevailed while the water was at 0°C; high counts appeared during rising and peak flows caused by June snowmelt and rain; a short "post-flush" decrease in bacterial counts took place as the runoff receded in early July; high bacterial counts were again found in the July-August period of warmer temperatures and low flows; and counts declined in September.

Concerning evidence that the forest floor can act as a bacterial filter, it has been found that snowmelt water that had percolated through a strip of forest on the bank of a reservoir contained fewer bacteria than water that had not passed through the forested strip.

The major sources of fluctuations in bacterial content (especially fecal coliform) that can lead to pollution levels in stream water are concentrations of any warm blooded animals on the watershed including man, livestock or big game animals. If bacterial content of stream water is to be kept below pollutional levels, strict attention must be given to all sources of potential contamination by living organisms

Integrating Watershed Management with the Multiple Use Concept

Watershed management is simply a component of the overall management plan and system to the wildland administrator actively pursuing a multiple use land management. Similarly, timber management, range management, and wildlife management are components of the management scheme. In many instances and situations, one or two of the wildland resource products may prevail due to local demands. However, even when one tree or a stand of timber is cut for sawtimber to attempt an increase in water production, herbage production and esthetic and recreational values will almost certainly be affected. Therefore, to effectively and efficiently practice one component of multiple use management, such as watershed management, the wildland administrator must be aware of the associated wildland resource management implications.

The Multiple Use Concept

In almost any discussion of wildland management problems, multiple use management is cited as a guiding principle. At times one gets the impression that multiple use is a panacea for all the problems of wildland administration. However, while there has been little difficulty in gaining general acceptance of the multiple use concept, it has had far less success as a working tool of management. Most people concede that timber or water production is not necessarily the sole production function of wildlands, and that forage, wildlife, and recreation should be considered in management decisions. But how much managerial effort should be allocated to each potential land use is a problem that wildland administrators have not always been able to resolve. Reconciliation of conflicting interests continues to be an important responsibility of wildland management agencies.

Meaning and Objective of Multiple Use

The term multiple use may be applied either to areas of land or to particular wildland resource products. When applied to land areas, multiple use refers to the production and management of various resource products or resource product combinations on a particular land management unit. The relation of several resource products on a management unit to one another may be competitive, complementary, or supplementary. A competitive relation exists between resource products when one must be sacrificed to gain more of another, as may occur between timber and water or between timber and forage. In complementary relations, both resource products increase together, as may occur between forage and water once the timber has been removed. A supplementary relation is one such that changes in one resource product have no influence on another, as may take place with livestock and wildlife within limited ranges or changes in forage production.

Conceivably, the relation of several resource products to one another on a particular land management unit may be competitive, complementary, and supplementary, depending on the area of management concern. In this situation, it is important for the wildland administrator to know what area of management concern confronts him. For example, if working with a supplementary relationship between timber and water, the administrator may not be able to influence water production by altering timber production, as illustrated in Figure 1.

When applied to a particular wildland resource, multiple use refers to the utilization of the resource products for various purposes. Water may be utilized for irrigation, industry, or recreation. Timber may be used for lumber, pulpwood, or Christmas trees. Forage may have value as feed for livestock and wildlife, or for watershed stabilization. Here again, the utilization of resource products may be competitive, complementary, or supplementary.

In practice, multiple use management involves both the multiple use of land areas and of particular wildland resource products. Demands on particular resource products (water) for specific uses (irrigation) places demands on the land areas where the resources are produced (watersheds).

The basic objective of multiple use management is to manage the wildland resource product complex for the most beneficial combination of present and future uses. The idea of maximizing the benefits from a given resource product base is not new, but it has become more important as competition for limited and interrelated resource products increases. These increased pressures forced Congress to enact the legislation necessary to establish multiple use as a policy on public wildlands. The multiple use policy for the National Forests was laid down by Public Law 86-517 of June 12, 1960, while Public Law 88-607 of September 19, 1964 outlines authority for multiple use management of land in the custody of the Bureau of Land Management.

The multiple use concept as described by law does not necessarily demand that every land unit in question should be utilized for all possible uses and resources products simultaneously. Instead, most public wildlands are utilized, to varying degrees, for a wide array of uses, as dictated by productivity and demand.

Multiple use land management of wildlands may be accomplished by any one of the following options, or by combinations of the three:

1. Concurrent and continuous use of the several wildland resource products obtainable on a particular land management unit, requiring the production of several goods and services from the same area.

2. Alternating or rotating the uses of the various resource products or resource product combinations on a unit.

3. Geographical separation of uses or use combinations so that multiple use is accomplished across a mosaic of units, any specific unit area being put to the single use to which it is most suited.

All of these options are legitimate multiple use management practices and should be applied in the most suitable combinations.

From society's point of view, regardless of the land management unit in question, multiple use involves a broader set of parameters that concerns the private investor. Generally, society is more interested in preserving wildland benefits for future generations, requiring investments beyond the dictates of limited business economics. On the other hand, the private investor makes decisions based upon relatively short-term profit motives commonly related to limited resource product uses. Effective multiple use management should accommodate the full spectrum of today's needs and provide for tomorrow's requirements.

Types of Multiple Use Management

There are two fundamental types of multiple use, land management resource-oriented and area-oriented. Resource-oriented multiple use management is dependent upon knowledge of interrelationships describing how the management of one resource affects the production of others, or how one use of a particular resource affects other uses of the same resource. Essentially, substitutions between resource products or resource uses, and the associated benefit-cost comparisons of alternative production combinations are taken into account. Resource-oriented management may deal with a single resource product with alternate uses, or with two or more resource products with alternative uses for each.

Resource-oriented multiple use management requires the understanding of wildland resource production capacities. However, to accomplish effective and efficient multiple use management, resources must not only be related to each other but also to the needs and wants of people. Area-oriented multiple use management meets this general objective through consideration of the physical, biological, economic, and social factors relating to wildland resource product development in a particular place. This type of management provides a framework in which information concerning the administration of land management units can be arranged, analyzed, and evaluated for the purpose of making sound management decisions. Area-oriented management draws that information needed to describe wildland resource product potentials from resource-oriented management, and then relates this to the dynamics of local and regional demands. Area-oriented management is not necessarily intended to replace other forms of management, but rather to complement it. Hopefully, this will help to close the gap between resource management and problems on the ground.

Integrating Watershed Management With Multiple Use

The problems of integrating watershed management within the multiple use concept, a necessity in effective and efficient wildland management, are not always fully realized by the wildland administrators. While these problems may often be structured in resource-oriented management objectives during the initial phases of management implementation, wildland administrators must continually be aware of area-oriented management implications, especially when management plans and systems are developed for application over large land areas. Numerous land management considerations, policy formulations, and institutional conflicts confront the wildland administrator attempting to integrate the component parts of multiple use land management. Although many of these issues are common to all components, several problems unique to watershed management implementation must be considered.

Land Management Considerations

Often, watershed management involves the development, evaluation, and application of land management systems designed to alter water production. The impact of management systems on a river basin may extend beyond simple attempts to alter the flow of water into downstream reservoirs. Many wildland resource products in addition to water are in demand from upstream lands, and these resource products must be allocated to maximize total benefits to society.

Land management systems designed to alter water production are commonly recommended by various interests groups. These systems often require sweeping modifications of vegetation on lands where the potential to alter water production is the highest. Some of these systems could jeopardize other land values, and some are irrevocable, at least in the short run, in that they can easily be made but cannot be undone if they turn out to be mistakes. Furthermore, in many cases, technological and economic guidelines have not been sufficiently developed to carry out the implementation of the system effectively and efficiently.

The implications of land management systems designed to alter water production are of particular interest to upstream land management agencies, such as the U.S. Forest Service, since these agencies are charged with administering a large portion of the potentially better water yielding areas. But, because management agencies like the U.S. Forest Service are committed to the concept of multiple use management, the implications of these land management systems extend beyond considerations of water production alone.

The problem is to determine advantages and disadvantages of land management systems designed to alter water production before the systems become operational.

Estimates of Wildland Resource Products

Measurements of the yields of all wildland resource products are necessary to determine their responses to land management systems. These products include water, timber, range for livestock and wildlife, and recreation. Consequently, estimates of water yield and quality before and after a management system has been imposed are desirable. Timber growth and quality measurements should also be obtained on a before and after basis. Likewise, records of forage production and utilization can subsequently be translated into beef gains and wildlife habita potential. Records of game and hunter use can be used to assess recreational values.

The measurements of wildland resource products on a management unit can be summarized i tabular form as a product mix. This table describes multiple use by quantitatively presenting al resource products derived from a particular area or class of land. Product mixes developed before land management system is implemented will form a reference for comparison with product mixe developed after implementation. These comparisons will show what is gained and sacrificed i multiple use terms, assuming that a resource product response to a system can be determined wit before and after measurements. Such comparisons form a basis for deciding among land managemen systems in terms of an appraisal of the advantages and disadvantages in resource product responses as shown in Table 1.

On one acre, if things remain as they are, T_0, the annual output will be 0.5 acre feet o water, 60.0 cubic feet of timber growth, enough forage for 1.5 pounds of beef gain, and 0.02 deer No timber will be cut. With conversion of moist sites to grass, T_0, 0.75 acre feet of water will b produced, 36.0 cubic feet of timber growth, enough forage for 10.5 pounds of beef gain, and 0.0 deer. One thousand one hundred board feet of timber will be cut. Columns T_2 and T_3 contain th elements of uneven-aged and even-aged management, respectively. The multiple use management proble is to determine what combination of these is the best. If T_0 is the best, as judged by an apprais of the advantages and disadvantages in resource product responses, the existing management syste should be continued.

Direct Costs and Benefits

Determining the costs of implementing and maintaining a land management system, as well a the direct returns associated with the management system, is prerequisite to efficient multiple us land management.

A large body of information on costs is available in the literature. Unfortunately, thes data normally reflect a particular economic situation and time, and cannot easily be adjusted t local conditions. Consequently, gross job time costs data in terms of physical input-outpu variables characterizing the management system and land area may be required. Inputs collecte include labor time, equipment time, direct supervision time, and materials. Outputs specify tota production as units thinned, cleared, etc. Costs are then determined by multiplying inputs b current wage rates, machine rates, and material costs. The sum of costs divided by the number o production units accomplished gives an estimate of the average unit costs for a management system.

Direct returns to the land management unit may largely be dependent on the sale of timbe removed in the initial establishment of the management system. Remember, calculations based on "saw-timber-only" market, as currently exists within many market areas, could become obsolete if pulpwood or veneer mill is installed. The presence of these additional outlets could alter th expected dollar returns by making previously unmerchantable material salable. Therefore, sinc market conditions can change quickly, and since they affect returns so significantly, the timber resource should be described in terms of multi-product potentials, providing timber quality an yield information for management and utilization decisions on a continuing basis.

Direct returns derived from other resource products, i.e., forage for livestock an wildlife, recreation, etc., could conceivably be determined by comparable objective analyse although these markets may be more poorly defined than timber.

The flexibility derived from the collection of objective cost-benefit data will allow lan management systems to be reevaluated as economic conditions change through time. Consequently, system initially considered economically impractical could become operational with a change in wage or machine rates, or with increased market outlets.

Economic Evaluations

To make an economic evaluation of a recommended land management system designed to alter water production, the following criteria could be selected to form a basis of choice:

1. Maximize benefits.
2. Maximize the returns on an investmnt.
3. Achieve a specified production goal at least cost.

Data required to satisfy the first two criteria include estimates of resource product values and physical responses resulting from land management redirection, and costs of implementing the management system. To satisfy the third criterion, goals often derived through the political process, must be established for various levels of production.

Economic evaluations essentially consist of an array of pertinent economic analyses designed to help wildland administrators make a better decision. Individual analysis may yield a one-answer solution to the problem of selecting a land management system that maximizes the returns to the land. A group of such analyses, based on different criteria, will result in an array of items for decision makers. Such an array may include:

1. Estimates of multiple use production associated with different land management systems.

2. Estimates of costs of management alternatives.

3. Least cost solutions for different goals of multiple use production.

4. Gross and net benefits associated with a range of management alternatives.

5. Investment returns and cost-benefit ratios associated with different management systems.

Policy Formulations and Institutional Conflicts

Given the above array of economic relationships, the watershed manager, acting as a wildland administrator, should be able to choose the best course of action in terms of implementing a land management system. However, it is anticipated that there may be policy issues and institutional cnflicts that must be resolved before a land management system becomes operational within the multiple use concept.

The question of who will pay for the establishment of a new land management system specifically designed to alter water production must be answered. The group of people that executes the system may not derive direct benefits from all of the multiple uses affected. For instance, it is questionable whether the U.S. Forest Service, who will carry out many of the operational programs necessary to implement a management system, will receive benefits commensurate with their costs. The role of downstream groups benefiting from increased water production from upstream lands will have to be established regarding costs.

The costs and benefits of a land management system designed to alter water production to society needs to be ascertained. Various viewpoints will need to be adopted so people can determine how a management system is going to affect them individually and collectively.

Local groups on or near the land area directly affected by a land management system will want to know how a program may affect them personally. Their viewpoint can be developed by the valuation of raw multiple use products on site or by the value added through manufacturing stages in the economic stream from resource to consumer within the local area. A single economic solution may not be suitable, but analyses reflecting the various viewpoints may yield the required answer.

Regional interests will probably bear a large portion of the investment in a land management system, and they will want to know how a program will affect them. A determination of the effects of a management system on a state's economy seems appropriate to this viewpoint. Finally, the national viewpoint must be the basis for some evaluation, primarily because most of the land that may be subjected to a management system will be federally managed, and the federal government will make at least a portion of the investment.

Perhaps the greatest problem facing the watershed manager pursuing multiple use land management is that of the development of an efficient institutional framework through which land areas subjected to the multiple use concept can be managed. A realistic multiple use management plan, such as that outlining a land management system designed to alter water production, must either work within the existing institutional structure, or modify it in order to be effective. An evaluation of the political and social organizations through which wildland resources are currently administered may suggest a necessity for institutional reform.

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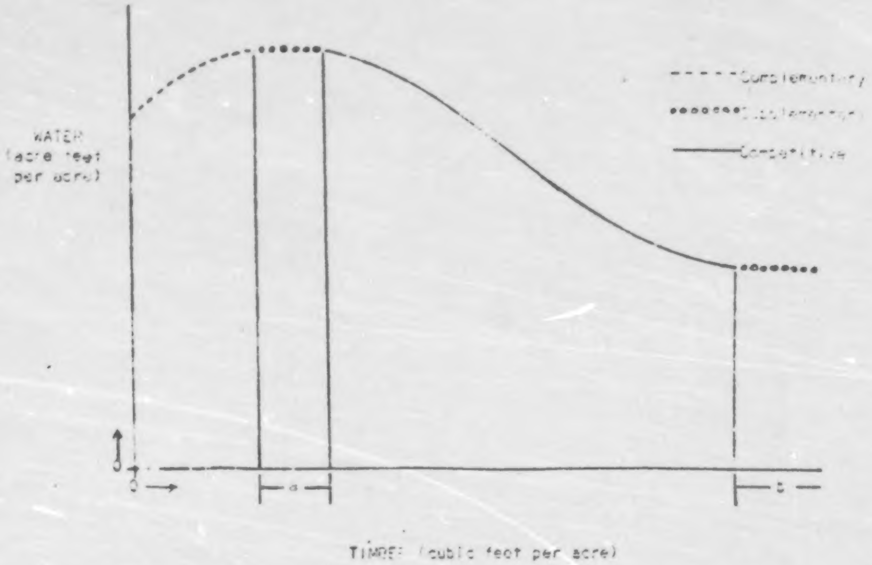

Figure 1. A hypothetical relationship between water and timber production on a land management unit, illustrating competitive, complementary, and supplementary relations. It is imperative that the wildland administrator ascertain which relation confronts him before implementing a land management redirection. Here, for example, the administrator will not be able to influence water production by altering timber production if operating in area a or b.

Table 1. Product mix vectors — Arizona ponderosa pine.*

Item	T 0 As Is	T 1 Convert	T 2 Uneven-aged	T 3 Even-aged
Water (ac.ft.)	0.5	0.75	0.54	.6
Timber growth (cu.ft.)	60.0	36.0	79.0	75.0
Livestock (lbs. gain)	1.5	10.5	0.3	6.0
Wildlife (no. deer)	0.02	0.03	0.03	0.03
Timber cut (bd.ft.)	0.0	1100.0	600.0	400.0

* Adapted from McConnen (1967) to represent ponderosa pine on the "high productivity sites" in Arizona.

Appendix A

Ecosystem Component Simulation

A project is currently under way to develop a prototype family of computer simulation models to aid natural resource managers in estimating the impacts of land management practices on ecosystems impacted by human activity. This family, called ECOSIM (Ecosystem COmponent SImulation Models), includes three general modules: (1) FLORA for estimating responses fo vegetation (e.g., forest overstory, herbaceous understory, organic material and open areas), (2) FAUNA for evaluating wildlife habitats, carrying capacities (wild and domestic), and population dynamics, and (3) WATER for assessing streamflow yield, sedimentation, and chemical quality. A command system enables users to operate all modules through a common language written in straightforward user terminology. This design provides flexibility in representing management activities by operating selected modules interactively on an appropriate data base.

ECOSIM is designed so that resource management professionals at remote locations can readily learn its use to obtain reliable predictions with readily available data and modest computer equipment. To date, ECOSIM has been developed to evaluate the effects of silvicultural practies on forest ecosystems. The methodology is readily adaptable to the severe problems of shifting agriculture, fuelwood harvesting and forest grazing practices which prevail on the upland watersheds in most of the developing nations. This project will modify and adapt the procedure to these problems. This appendix highlights ECOSIM and outlines the direction of future development.

Flora Module

At present, the FLORA module consists of computer simulators that predict the growth, yield, and diversity of forest overstories, the production and (to some extent) composition of herbaceous understories, and the development and accumulation of organic material on the forest floor.

Forest Overstories

The component simulators designed to estimate the growth and yield of forest overstories generally fall into two categories: first, models that are broadly structured to represent a wide variety of tree species (or tree species groups); and second, models that are specifically structured to represent a particular tree species (or tree species group).

Within the first category, three simulators have been developed, or are presently under development. These simulators, called TREE, STAND, and FOREST, will estimate the growth and yield of an individual tree, a forest stand (by definition, a community of trees possessing sufficient uniformity as regards composition, age, spatial arrangement, or condition to be distinguishable from adjacent communities), and an entire forest property, respectively.

TREE is an interactive modification of a computer model that simulates the growth of an individual tree from knowledge of diameter, height, and volume (Pierce 1976). In addition, one can easily see how individual tree growth is influenced by tree size and age. While this is not a new concept in forestry, the approach exemplified by TREE differs from that of others (Beck 1974, Lin 1974, Burkhart and Strub 1974) who have employed mathematical formulas to simulate tree growth phenomena.

The primary reason for including TREE in the ECOSIM family of models is to analyze changes in tree growth as influenced by alternative silvicultural management practices. Such assessments furnish direct insight to the understanding of the dynamics of even-aged and uneven-aged forest stand developments.

STAND, is structured to estimate the growth and yield of forest stands comprised of single tree species (ponderosa pine, slash pine, aspen, etc.) or a mixture of tree species (southwestern mixed conifers, shortleaf-loblolly pine, balsam fir-black spruce, etc.). In essence, the mensurational input to STAND to date has involved the simplification of prior stand projection methods applicable to uneven-aged forest stands (Hasel 1961, Larson and Gogorth 1970). Subsequent work will be directed toward considerations of growth and yield predictions in even-aged forest stands.

The simulation objective of STAND is to predict the growth (both gross and net) and yield of forest stands prior to and, if appropriate, following the implementation of various silvicultural managemment practices. Inputs to this modular component include a listing of trees per acre by size class, and associated diameter growth rates and volume expressions. As management is prescribed to change these inputs, post-treatment growth and yield are interactively generated. Silvicultural management practices that can be simulated within STAND represent an array of viable options for the different forest stand compositions being considered.

Outputs derived from STAND, including summaries of basal area levels through time prior to and following a management redirection, are readily used by other modular components in FLORA and by other modules in ECOSIM. As the manipulation of forest overstories is a primary management activity affecting many aspects of an ecosystem, such interfaces among modular components are critical to realistic simulation of an ecosystem's overall behavior.

FOREST is being assembled as an interactive version of other general computer models that have been structured to simulate the growth and yield of single or mixed tree species, and even-aged or uneven-aged forest properties (Botkin, Janek, and Wallis 1970, Ek and Monserud 1974). This modular component addresses topics of forest growth and yield such as seed production, dispersal, and germination, as well as competition, mortality, and stocking manipulation by man.

In concept, inputs to FOREST include a set of real or generated tree locations and associated tree characteristics. Each tree is then grown for a specified number of projection periods, based on potential growth functions modified by competition measures synthesized from relative tree size, crowding, and shade tolerance. Mortality is generated stochastically and depends, in part, upon the competitive status of the individual trees. Reproduction is represented by simulating seed production and germination and, if appropriate, sprout production from the forest overstory. Numerous site alterations and harvesting options can be specified as the forest develops over time. Outputs from FOREST will be in the form of periodic tables displaying data on stocking, mortality, and yield for an array of primary wood products and total biomass.

FOREST is initially being written as a set of individual computer subroutines, each of which correspond to particular stages or processes in the development of a tree, forest stand, or forest property. Each subroutine is being designed to facilitate inputs by non-computer-oriented users not necessarily familiar with computer technology or the operational details of the original computer models.

An excellent example of a simulator designed to estimate the growth and yield of a particular tree species (or tree species group) within the ECOSIM family of models is PIPO (Larson 1975, Larson 1978). This modular component is an interactive management simulator for ponderosa pine stands. Users can initialize the model by selecting prestored stand tables, by entering tallies from point sample inventories, or by entering the number of trees per acre by size class. Then, harvests can be specified at intervals through a sequence of questions and answers to meet a particular management objective. PIPO can be used to determine stand density levels or cutting practices for desired volume production, rotation lengths, and sustained yields.

In addition to computer simulators that predict growth and yield, a modular component is under development in FLORA to estimate the diversity of (and within) forest overstories. This component, called DIVER, has two primary options with respect to manipulations of forest overstories – clearing and thinning. The clearing option derives a diversity index that represents the edge irregularity of a clearing (or other type of forest opening). The thinning option calculates a diversity index that represents the proportion of an area that is stocked to different forest density levels.

The diversity index derived by the clearing option is based on a previously reported analytic model that quantifies wildlife habitat (Patton 1975). The geometric shape with the greatest area and the least perimeter or edge is a circle. If the ratio of circumference to area of a circle is arbitrarily given an index of 1, a formula can be used to compute an index for comparison of any area with a circle. The higher index value is above 1, the greater the irregularity, and by definition within DIVER, this value is an expression of diversity.

In the thinning option, the calculated diversity index is obtained through solutions of forest stocking equations that are developed for the particular forest type and size class distribution being evaluated. Stocking equations define exceedance curves which describe the proportion of a forest area (the dependent variable, expressed in percent) that is stocked to minimum basal area levels (the independent variable). Values that represent minimum basal area levels for alternative silvicultural management practices are the required inputs to the simulator. To date, the set of stocking equations in the DIVER thinning option only characterize southwestern ponderosa pine forest conditions (Ffolliott and Worley 1973). Work is now under way to expand this option for use in other ecosystems.

Herbaceous Understories

A compute simulator has been structured with the FLORA module to estimate herbage production from knowledge of forest overstory parameters, precipitation amount, and if appropriate, time since the implementation of a silvicultural management practice. (As used in ECOSIM, herbage refers to all understory species, while forage refers to that component of the understory that is considered palatable for a given animal species.) Depending upon the particular simulation objective, a user may operate this component, called UNDER, individually or as part of an interfaced package. In the latter instance, outputs from other modular components in FLORA and other modules in ECOSIM are utilized as inputs. An interactive language is used in either case.

Many of the previous attempts at developing computer simulation techniques to estimate herbage production have been dependent, primarily, on input variables depicting forest density conditions (Myers and Currie 1970, for example). While this approach remains viable and has been utilized in several UNDER subroutines, the herbage production simulator will eventually also utilize knowledge of forest overstory growth. Estimates of herbage production that are based on knowledge of this variable appear consistently of higher precision than those based on knowledge of forest density alone.

Subsequent additions to UNDER will facilitate partitioning of simulated herbage production into (at least) three categories: grasses and grass-like plants, forbs and half-shrubs, and shrubs.

Organic Material

Two modular components describe the development, accumulation, and distribution of organic material on a forest floor. One component, referred to as FLOOR, estimates the accumulation of tree needles and leaves (by layer of decomposition) on a forest floor at a point-in-time, the rate of accumulation with respect to time, and the spatial distribution in space. Another component, called CROWN, predicts the magnitude of tree crown and branchwood accumulation associated with alternative silvicultural management practices being simulated. These models are designed such that they may be executed individually or as an interfaced package.

FLOOR is an interactive component which outputs parameters that describe the development, accumulation, and distribution of tree needles and leaves as a function of forest density levels (usually expressed as basal area) for different management practices. In terms of accumulation at a point-in-time, the following individual layers are considered: litter, fermentation, humus, and total. To date, the rate of litter accumulation is the only FLOOR simulation output that provides a time dimension. Regarding spatial distribution, only the total forest floor (all layers) is represented.

While in the early stages of development, CROWN is intended to present knowledge of adjusted crown volumes by area for a given forest stand prior to the implementation of a silvicultural management practice. This will, hopefully, provide a reference point to assess the quantity of tree crowns and branchwood that will occur as logging residues on the forest floor after implementation.

Fauna Module

Presently, the FAUNA module includes interactive computer simulators that describe the habitat quality for a variety of animal species, the potential animal carrying capacity of an area, and the dynamics of selected animal populations within specific ecosystem situations.

Habitat Assessment

Simulators that assess habitat quality fall into two categories - models broadly structured to represent a variety of animal species (including game, nongame, and domestic) and models specifically structured to represent a particular animal species.

The primary example of a modular component in the first category is HABRAN (HABitat RANking). In essence, this component involves the synthesis of ranked response predictions which, in turn, can be summarized and arrayed as pattern recognition models. Within HABRAN, animal habitats are assigned numerical values ranging from 0 to 10, with habitat quality in an ecosystem increasing with numerical value. The specific assignment of these values is achieved through analyses of functions that relate habitat preference to readily available inventory-prediction parameters, the magnitude of which are altered by alternative silvicultural management practices. By comparing numerical habitat quality values for existing conditions with those predicted for habitats modified by management re-direction, either an increase (+), a decrease (-), or no change (0) is determined. Then, a matrix of pluses and minuses, and zeros arrayed for all animal habitats and management alternatives of interest (by definition, a pattern recognition model) can be displayed to provide insight as to comparative management impacts.

Initial efforts in the development of HABRAN, centered in the southwestern ponderosa pine forest ecosystem, have been directed toward: big game (specifically deer and elk); small game (including tree squirrels and cottontails); small rodents (such as mice, chipmunks, and ground squirrels); nongame birds species (as grouped by feeding categories); and domestic livestock (including cattle and sheep).

The HABRAN component of the FAUNA module is, in a sense, a first-level-of-interest assessment of the impacts of alternative silvicultural management practices. In many instances, this sort of analysis may be all that is required. However, if estimates of carrying capacities and animal distributions are needed, other modular components may be called into play.

Other habitat quality simulators broadly structured to represent a variety of animal species in ECOSIM that are in the early stages of development include: FEATUR, which is evolving from the feature species concept of timer and wildlife management (Holbrook 1975); and LIFE, which is based on the notion of life forms as related to community and successional stage of habitat dynamics (Thomas et al. 1976). These two components, along with HABRAN, will provide users with a choice of approaches to the simulation of habitat quality.

Within the category of FAUNA simulators designed to represent a particular animal species, perhaps the best present example is SCAB, an interactive version of a system for rating habitat quality for Abert Squirrel in southwestern ponderosa pine forests (Patton 1977). This system brings together information of food, cover, and diversity to produce a simple rating of habitat from poor to excellent. In brief, ratings are based upon: food – the occurrence of cone producing ponderosa pine and acorn producing Gambel oak (often found intermixed in southwestern ponderosa pine forests); cover – forest density and tree size criteria; and diversity – combinations of tree groups, dominance, and spacing. Changes in food, cover, and diversity resulting from the implementation of a silvicultural management practice are reflected by changes in the rating of habitat quality.

Animal Carrying Capacity

In the modular component that has been structured to predict animal carrying capacity, referred to as CARRY, herbage production (entered as a direct input by the user or obtained from the herbage production simulator) is partitioned into usable forage for deer, elk, cattle, and sheep. Appropriate plant species to include in each forage component was ascertained from existing literature relevant to the preferred foods for these animals, along with information about appropriate or proper utilization percentages.

It has been assumed that the proper use factors to be applied in CARRY will be introduced by the use in an attempt to meet specific management objectives. It may be necessary, for example, to reduce a proper use factor on a particular range that has been sujbected to prolonged overgrazing pressures. As baseline information relating to proper use factors for deer, elk, cattle, and sheep increases, the ability to predict carrying capacities will improve accordingly.

The amount of usable forage required per animal unit month (AUM) for the animal species being considered in the prototype model was derived from a base value of 1.0 for cattle. Specifically, animal unit equivalents for deer, elk, and sheep, as determined from existing literature, were: 0.19 for deer, 0.50 for elk, and 0.15 for sheep. Assuming 750 pound of forage per cattle unit month (again, as determined from available information), approximately 140, 375, and 112 pounds of forage are required per AUM for deer, elk, and sheep, respectively.

As an alternative to the above-mentioned approach to obtaining AUM values, the user can explicitly (and directly) input AUM values, assuming that knowledge is available to do so.

With respect to the number of months that deer, elk, cattle, and sheep will actually be consuming forage on any tract of rangeland, this value is quite variable depending, in part, upon weather factors that characterize the particular ecosystem and year of simulation (time of snowfall in the autumn, time of snowpack disappearance in the spring, etc.). At best, only estimates based on local knowledge of average situations in the long-run can be made. However, to provide a point-of-departure in utilizing CARRY, specific forage consumption time durations have been selected. It should be emphasized that the user can readily override these default duration values to more accurately reflect local conditions if better information is available.

At this time, relatively little can be said about possible constraints that may affect the distribution of animals that are considered by CARRY. While it is known that various factors may restrict (or at least modify) animal movements, explicit identification and subsequent quantification are currently difficult. Conceivably, portions of a tract may be eliminated from use because of movement constraints (physiography, fences, etc.), which may necessitate appropriate reductions in animal stocking rates.

The effects of alternative silvicultural management practices on animal carrying capacities of a given area are primarily evaluated through predictions of changes in the level of herbage production. As forest overstories are reduced in density, a corresponding increase in herbage production commonly occurs. The increased production of herbage is then partitioned into forage which, in turn, is converted into AUM values that are distributed over the range.

Population Dynamics

Although still in the formulation stage, an interactive population dynamics model, called

DYNAM, is intended to predict the impacts of silvicultural management practices on the reproduction, growth, mortality, and structure of selected animal populations. More specifically, this modular component is to predict the manner by which a given population, specified by the user as reflecting existing conditions within an ecosystem, will respond to changes in food, cover, and diversity that are attributed to management re-direction.

The initial effort is to synthesize a branch of DYNAM to estimate the effects on mule deer population of silvicultural management practices imposed in southwestern ponderosa pine forests. The subject forest types are essentially summer range, therefore, the model will emphasize that segment in the life of a defined mule deer population. Hopefully, once developed, the generalized structure of this model can be utilized to represent other animal populations in other ecosystems.

Water Module

At this time, the WATER module is comprised of generalized components to predict streamflow yield, as well as suspended sediment and chemical quality of streamflow.

Streamflow Yield

The requirement for a small model with simple data needs to represent streamflow yield has led to the development of YIELD. Within YIELD are several water yield prediction components which may be inserted in the ECOSIM package to handle the prediction of water yield.

One modular component, which in essence is a modification of a previously developed computer model that describes hydrologic behavior on forested watersheds (Rogerson 1976), simulates a water balance on a daily basis. It is designed such that data inputs required from the user are few and commonly available.

Another component is a water balance model developed to handle various depths and textures of soil, and either coniferous or deciduous forests.

Coupled with these water yield components may be other models which predict the accumulation and melt of snow. There are currently two models which may be utilized to predict water yield from snow. One is a model based on degree day concept of snowmelt. Another is a routine developed from a modification of a documented computer model of snowmelt (Leaf and Brink 1973, Solomon et al. 1976). This routine, which provides for modeling intermittent snowpacks, is dependent on four daily input variables: maximum and minimum temperatures, precipitation, and shortwave radiation. Initializing requires only limited knowledge of watershed and snowpack parameters.

The assemblage of the water yield model, to predict yield in the non-snow setting, and one of the snow handling models, for snow conditions, produces a general model which predicts water yield from an area for all times of the year.

The primary "driving variable" within YIELD is daily precipitation. The primary initialization variable is a measure of forest density conditions, expressed here in terms of basal area. Outputs from the model are values representing daily runoff, change in soil moisture, evapotranspiration, melt and deep seepage. Linkages to other components in ECOSIM are used to obtain basal area, while the outputs of daily runoff are, in turn, inputs to the components used to predict sediment and chemical quality.

Sedimentation

One modular component in WATER, called SED, predicts the amount of suspended sediment in streamflow. While structured to facilitate extrapolation to other ecosystems, the present version of this interactive simulator relies on relationships developed in an assessment of suspended sediment data collected from several watersheds in the ponderosa pine forests of central Arizona.

The model is structured to offer a choice between two alternative sets of input data requirements. As based on the data which a user may have available, he will select one set to be used. Input data, which either represents forest density conditions or spatial distributions of organic materials on a forest floor, are entered directly by the user or generated by STAND or FLOOR, respectively. The other data input needed, streamflow yield, may be obtained from YIELD. Th program outputs the maximum concentration of suspended sediment each day, the maximum streamflow discharge, and the total weight of suspended sediment produced under alternative silvicultural management practices simulated.

Chemical Quality

As an intial attempt at developing a modular component to predict the chemical quality of streamflow, a simulator has been devised to estimate maximum concentrations and daily volumes of selected dissolved chemical constituents. This component of WATER, called CHEM, is specifically aimed at providing descriptions of the chemical quality of low-volume, winter (snowmelt runoff) discharges from watersheds characterized by southwestern ponderosa pine forests and southwestern mixed conifer forests. The primary "driving variable" is streamflow quantity, the magnitude of which will often vary with alternative silvicultural management practices. This input variable can be entered directly by the user or obtained from outputs from YIELD.

Presently, thirteen constituents are estimated within the CHEM framework: calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{++}), choride (Cl^{-}), sulfate ($SO_4^{=}$), carbonate (CO_3^{-}), bicarbonate (HCO_3^{-}), fluoride (F^{-}), nitrate (NO_3^{-}), phosphate (PO_4^{-3}), total soluble salts, hydrogen ion (ph), and conductivity. Efforts are under way to include other water quality parameters, such as heavy metals (Zn, Fe, Cu, Pd, Cd, etc.) and dissolved oxygen.

The Command System

The command system of ECOSIM is largely dispersed into the respective modules. In fact, there is little evidence of a main command system in the overall operation of the ECOSIM family of models. Initial selection of which modules and components are to be used and subsequent assignment of default values needed in the operation are handled by the command system. Also, timing and sequencing of operation of individual modular components are carried out by the system. Additionally, summary displays (tables, graphs, maps, etc.) of the simulation results are achieved through the command system.

All of the modules in ECOSIM have been structured to have three modes of operation: initialization, cycling in time, and summary. In the initialization mode, all needed input data are either introduced directly by the user or entered from stored files. The second mode of operation is a cycling in time of the processes being simulated (daily streamflow, yearly forest growth, etc.). Finally, the third mode of operation is summary and, if appropriate, other activities at the end of a simulation problem.

When a user informs the command system which modular components are to be operated, he also states when they are to be used in the simulation problem. For example, the component CHEM may be required to operate only in the fifth year of simulation, while all other components may be operated every year. The command system stores this directive and acts accordingly.

The entire system is designed to operate with minimal input data. Default values are offered with nearly all of the interactive questions posed so that, whether or not the user has the required data or reason for overriding the default values, simulation can still proceed. Similarly, if a module or component is not directly included in a simulation problem, default values are loaded into the system to provide estimates of needed parameters normally obtained as output from the unused modular components.

After the system cycles through the specified number of simulation years, individual models are entered into the summary mode of operation. Any needed computations to allow display summaries of the operation to be output are carried out at this point. Output summaries may be obtained either on a local computer terminal or at a central computer location. These summaries may be brief or detailed, depending upon the user need. In general, the parameters shown are representative of the various modules and components used in the problem. If a component is not used and default data are utilized, the parameters for the unused component will not alter the display.

Future Directions

As currently conceived, future work in the development of ECOSIM will follow two directions: synthesis of other modules and components, and extrapolation of the interactive system into other forest and range ecosystems.

While in various stages of development, several other modules and components are recognized as part of the ECOSIM family of computer models. For example, to facilitate overall planning with respect to a particular simulation problem, a module called PLAN is being structured to generate a PERT network of activities necessary to reach an objective. Another module, referred to as AREA, calculates the adjusted surface area of management units within an ecosystem, correcting for sloping or broken terrain.

As knowledge of site quality is required as input to some modular components in ECOSIM, a module called SITE is under development to generate site quality directly (through estimation of site indices) or indirectly (through analyses of plant indicators, physiography, soil surveys, etc.). Outputs from this module will describe productivity potentials for both forest overstories and herbaceous understories.

To evaluate depth and quality of view within an ecosystem in terms of current and, if appropriate, anticipated conditions, a module named SEEN is being evaluated as part of ECOSIM. Another module, called FIRE, predicts the probability occurrence of wildfires of given intensities from knowledge of fuel properties and sequencing of meteorological events; this module also estimates the impacts of fire on an ecosystem.

SNOW is a module that interactively simulates the dynamics of snowpack accumulation and melt within forests comprised of trees in varying spatial arrangements. ROAD allows for predictions of sediment loads resulting from the construction of roads with alternative design criteria.

To further aid managers and planners in analyzing land use alternatives, a module that facilitates the development and subsequent display of basic production economics models (production functions, product-product relationships, etc.) has been synthesized. This module, referred to as ECON, also includes components that represent various LP and Goal programming techniques. Other modules and components will be considered within ECOSIM to more completely provide socio-economic simulation capabilities.

The primary emphasis in the intial developmental work on ECOSIM has been placed on simulation within three specific forest ecosystems: southwestern ponderosa pine, southwestern mixed conifer, and southeastern loblolly and slash pine. Current plans are to extend this work in to other forests and, as the need arises, into range and arid ecosystems.

Extrapolation of the ECOSIM concept into other ecosystems is often made easier by the generalized structure commonly followed in much of the initial development. In fact, many of the modular components that have been synthesized only require "localization" of coefficients for extrapolation. Others, particularly those structured to represent an explicit plant or animal species, are only appropriate for use in simulating those ecosystems in which they occur and must be replaced by other species - specific models that characterize other ecosystems under consideration. However, even here, replacement is relatively easy within the overall structure of the command system.

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Erosion Processes and Control

by
B. Heede

Gully Development and Control

Historical Background

Early man was less mobile and more dependent on the surrounding land than his modern descendant. In many desert and semidesert regions, he not only learned to live with gullies, but utilized them for the collection of water and the production of food. Such desert agriculture was practiced in North Africa, Syria, Transjordan, southern Arabia, and North and South America. Thus, many areas in the world once supported more people than today. The Sierra Madre Occidental, Mexico, had a much higher population density 1,000 years ago than at present (Dennis and Griffin 1971), as did the Negev Desert in Israel (Evenari 1974).

Gully control on these ancient farms was not an end in itself, but a means for food production. Evenari et al. (1961) found well-defined "runoff farms" in the Negev Desert of Israel dating back to the Iron Age, 3,000 years ago. The climate, undoubtedly not different today, is characterized by an average yearly precipitation of 95 mm (3.7 inches), most of which falls in relatively small showers. Precipitation exceeds 10 mm (0.39 inch) on an average of only 2 days per year. Still, runoff farms, using check dams and water spreaders in wadis, gullies, and on hillsides, were able to support dense populations until the Negev was occupied by nomadic Bedouins after the Arab conquest in the 7th century A.D.

At least 900 years ago, the aborigines of the northern Sierra Madre Mountains of Chihuahua and Sonora, Mexico, developed an intensive field system by altering the natural environment with the help of trincheras (Herold 1965). Trincheras of the Sierran type -- check dams built from loose rock — created field and garden plots within gullies and valleys by sediment accumulation, increased water storage within the deposits, and spread the flows on the deposits during storms. Similar but less developed systems were built sporadically in Arizona, New Mexico, and southwestern Colorado. About 1450 A.D. this flourishing agriculture disappeared.

With the age of industrialization, man lost his close dependence on the land. Population densities increased, land was fenced, and roads and communication systems mushroomed. Ths rapid change caused a different philosophy in the approach to gullies. Gullies were visualied as destroyers of lives and property, and as barriers to speedy communication. It is not surprising, therefore, that the first textbook on gullies or torrents, published in the 1860's in France, dealt with control only. Others followed quickly in Austria, Italy, Germany, and later in Japan.

It is not surprising that our knowledge on the mechanics of gullying is meager if we consider that, during the last 100 years, torrent and gully control were emphasized. Gully control research focused on engineering aspects — structural dimensions, types of structures, and adaptation of advances in civil engineering elsewhere. When in the middle 1950's interest was awakened in gully processes, efforts concentrated on mathematical and statistical, rather than physical, relationships.

The time has come to concentrate our efforts on understanding gully mechanics, and to reassess our philosophy on gully control. The objectives must be broadened beyond those of defense, and incorporate those of agricultural production, water yield, and environmental values. This task will not be easy, and in many cases tradeoffs will be required.

In areas of food shortage, the most pressing objective in gully control may be agricultural production. Food-short areas are often arid or semiarid, where gullies are the only streambeds supporting flow at times, and gully bottoms are closest to the low-lying water table. Gully flows as well as moisture storage both were utilized for plant growth by ancient man. Modern man may have to relearn the forgotten art of gully management in desert farming. This possibility is better for many developing countries; in highly industrialized countries, the present cost-price structure will seldom permit successful gully management for food production in deserts and mountain lands.

In the United States, however, gully management has been successfully practiced on agricultural lowlands at least since the 1930's, when conservation farming was introduced on a large scale. Farmers converted gullies into grassed waterways to serve the dual purpose of safe conveyance of surplus irrigation water and forage production. Often the federal government subsidized this work by extending technical and monetary help.

In contrast to agricultural lowlands, we know very little about gully management on mountain lands, where we have been mainly concerned with control. In the United States, a first approach to gully management on mountain slopes was Heede's (1968a) installation of vegetation-lined waterways in the Colorado Rocky Mountains. Converted areas lost 91 percent less soil than untreated gullies, and the unpalatable plant cover, consisting mainly of sagebrush, was changed to a palatabe one, adding to the grazing resource.

In Italy,, intensive hand labor, plowing, and manmade torrent streams reshaped gullied mountain slopes of the Apennines into gentle hillsides that could support pastures, vineyards, and orchards. The reshaping, called hydraulic reclamation (Heede 1965a), was justified by efforts to place Italian agriculture on a competitive basis when it would join the Common Market Community in the late 1960's (Heede, 1962).

Modern check dam systems can also benefit water yield. Brown (1963) reported on the conversion of ephemeral flows to perennial streams below check dams. Heede (1977) obtained perennial flow 7 years after installation of a check dam system where only ephemeral flow had occurred during the previous 50 years. It is postulated that this change is due to water storage in the sediment accumulations above the dams. Considerable vegetation develops within the gullies as well as on the watershed. Although this additional vegetation undoubtedly uses water, the evapotranspiration loss is more than offset by increased soil infiltration rates, resulting from vegetation cover improvement, which benefit soil water storage at times of high flows. The duration of significant flows increased, but total water yield did not.

The environmental value of gullies is assessed differently by different people. To some, gullies may represent a typical landform of the Old West, a dear sentiment, adding to environmental quality. To them, gully control should be attempted only if needed to meet pressing land management objectives. To others, gullies may offer only an unsightly scene, and the conversion of raw gully walls into green stable slopes is a desirable goal. Our approaches to gully management must therefore remain flexible.

It is the objective of this paper to show progress and limits in our knowledge of gullies and their control, and thus to help the land manager achieve his goals.

Scope

This paper attempts to summarize the available body of knowledge and hypotheses on gully formation and control. As illustrated by the historical development of gully management, gully control currently comprises the larger body of knowledge. Of necessity, the discussion of gully control will be based mainly on works in the Colorado Rocky Mountains, where considerable effort has been invested since the work of the Civilian Conservation Corps in the 1930's.

Gully Formation

Processes and Morphology

Discontinuous Gullies

Leopold and Miller (1956) classified gullies as discontinous or continuous. Discontinuous gullies may be found at any location on a hillslope. Their start is signified by an abrupt headcut. Normally, gully depth decreases rapidly downstream. A fan forms where the gully intersects the valley. Discontinuous gullies may occur singly or in a system of chains (Heede 1967) in which one gully follows the next downslope. These gullies may be incorporated into a continuous system either by fusion with a tributary, or may become a tributary to the continuous stream net themselves by a process similar to stream "capture." In the latter case, shifts on the alluvial fan cause the flow from a discontinuous gully to be diverted into a gully, falling over the gully bank. At this point, a headcut will develop that proceeds upstream into the discontinuous channel where it will form a nickpoint. Headward advance of the nickpoint will lead to gully deepening.

A chain of discontinuous gullies can be expected to fuse into a single continuous channel. Heede (1967) described the case history of such a fusion. Within three storm events of less than exceptional magnitude, the headcut of the downhill gully advanced 13 m to the next uphill channel, removing 70 m^3 of soil and forming one gully.

Vegetation types on the eastern and western flanks of the Colorado Rocky Mountains have not controlled the advance of headcuts of discontinuous gullies. Ponderosa pine and Douglas fir types, both with understory of grasses and other herbaceous vegetation, grew on the eastern flank; grass and sagebrush dominated the western flank. Since dense root mats of all these species occur at a depth below ground surface of only 0.3 to 0.6 m, undercutting by the waterfall over the headcut lip renders the mats ineffective.

Investigation of valley fill profiles and discontinuous gullies in Wyoming and New Mexico showed that discontinuous gullies formed on reaches of steeper gradient within a valley (Schumm and Hadley 1957). The authors postulated that overly steep gradients within alluviated valleys could be explained by deficiency of water in relation to sediment. In arid and semiarid areas, water losses along stream courses are well known (Murphey et al. 1972). The maintenance of stable alluvial streambeds is related to the quantity of water and the quantity and type of sediment moving through the system (Schumm 1969).

On the Alkali Creek watershed, evidence suggests that discontinuous gullies began to form at locations on the mountain slopes that were characterized by a break in slope gradient. This observation coincides with Schumm and Hadley's (1957) survey on valley floor and discontinuous gully profiles on Wyoming and New Mexico, and with Patton and Schumm's (1975) investigations of gullies in the oil-shale mountains of western Colorado. There, the breaks in valley gradients constituted a critical oversteepening of the valley slope. The oversteepening was the product of tributary streams that deposited large alluvial fans on the valley floor. Since flow data were not available, Patton and Schumm related the valley slope to drainage area. Discriminant-function analysis showed that, for areas larger than 10 km^2, a highly significant relationship existed between slope gradient, drainage area, and gullying. Discontinuous gullies occurred only above a critical slope value for a given area. The authors suggested that the results may be applicable only for the study region, since climate, vegetation and geology were considered constants. Yet for this particular region, the land manager obtained a valuable tool that tells him where discontinuous gullies may form.

The initiation of a discontinuous gully may also be explained by piping collapse (Hamilton 1970). Leopold et al. (1964) reported soil pipes to be an important element in the headward extension of this gully type. Since soil piping may be related to soil sodium, soil chemistry must also be regarded as a factor in gully formation, as demonstrated on the Alkali Creek watershed (Heede 1971). Piping soils, which caused gully widening and the formation of tributary gullies, had a significantly higher exchangeable sodium percentage (ESP) than nonpiping soils. The sodium decreased the layer permeability of the soils by 88 to 98 percent. Other prerequisites for the occurrence of pipes were low gypsum content, fine-textured soils with montmorillonite clay, and hydraulic head.

Older soil piping areas showed that extensive presence of pipes leads to a karstlike topography. The mechanical breakdown of the soils under such conditions facilitates leaching of the sodium from the soils, which in turn benefits plants. The new topography, characterized by more gentle gully side slopes compared with the former vertical walls of sodium soils, permits increased water infiltration, and natural rehabilitation of the gully by vegetation.

Dontinuous Gullies

The continuous gully begins with many fingerlike extensions into the headwater area. It gains depth rapidly in the downstream direction, and maintains approximately this depth to the gully mouth. Continuous gullies nearly always form systems (stream nets). They are found in different vegetation types, but are prominent in the semiarid and arid regions. It appears that localized or regional depletion of any vegetation cover can lead to gully formation and gully stream nets, if other factors such as topography and soils are conducive to gully initiation. Several studies have demonstrated, however, that vegetation and soil type predominantly influence the morphology of gullies.

Schumm (1960) found that, in western channels, the type of material in banks and bottoms controls the cross-sectional channel shape. When the mechanical analysis of the soils was related to the width-depth ratio (upper width versus mean depth), linear regression indicated that increases in the ratio conformed with the increases of the average percent sand in the measured load. This relationship was also established by the Soil Conservation Service at Chickasha, Oklahoma (unpublished report). On Alkali Creek, where extensive sampling showed no significant differences in the texture of the soils, meaningful correlations between the width-depth ratio and thalweg length could not be established (Heede 1970).

Tuan (1966) reported, in a critical review of literature on gullies in New Mexico, that channels developed in a semiarid upland environment were of moderate depth, and cut into sandy alluvium. Deep trenches were rare. The influence of sand in gully bank material on sediment production was shown when upland gullies were studied in the loess hills of Mississippi (Miller et al. 1962). They found that the annual volume of sediment produced ranged from 0.091 to 0.425 m^3 per hectare of exposed gully surface. The lower rate was associated with an average 6-m vertical gully wall having a low percentage of uncemented sand, while the higher rate was found in gullies with 12 m vertical walls and a high percentage of uncemented sand. As illustrated by gully erosion on the Alkali Creek watershed, sediment production may also be related to the chemical composition of the soils (Heede 1971).

That vegetation surrounding a gully may exert stronger influences on the channel morphology than the soils was shown for small streams in northern Vermont (Zimmerman et al. 1967), and also for a large gully in California (Orme and Bailey 1971). The California gully occupied a 354-ha watershed in the San Gabriel Mountains. In an experiment to increase water yield, the riparian woodland was removed and replaced by grasses. Two years later, a wildfire destroyed all vegetation on the watershed, and 57 ha of side slopes (16 percent of total area) were seeded to grass. The vegetative conversion was maintained by aerial sprays with selective herbicides. When high-intensity storms hit the watershed 6 and 9 years after conversion, stream discharge rates and sediment loads increased to previously unknown magnitudes. Changes in longitudinal profile and channel cross sections were spectacular. The gully "survived" as a relict feature partially clogged with storm debris, but had not regained its hydraulic efficiency by mid-1971.

In the Vermont streams, encroachment and disturbance by vegetation eliminated the geomorphic effect of channel width increase in the downstrem direction, a normal stream behavior. In contrast, on the Alkali Creek watershed where gullies did not experience severe encroachment or disturbance by the sagebrush-grass cover, this geomorphic effect was eliminated by local rock outcrops and soils with low permeability due to high sodium (Heede 1970).

To establish gully morphology and possible stages of gully development, Heede (1974) analyzed the hydraulic geometry of 17 Alkali Creek gullies. Stream order analysis showed that 57 percent of the area of a fourth-order basin was drained by first-order streams. This is contrasted to 1 percent, the average for similar river basins in the United States (Leopold et al. 1964). Since the Alkali Creek gully system is still in the process of enlargement toward headwaters the drainage area of the first-order streams will decrease with time. The longitudinal profiles of the gullies exhibited weak concavities, and it was argued that concavity would increase with future gully development.

The shape factor of the gullies, relating maximum to mean depth and expressing channel shape, had relatively high values (average 2.0). These values represent cross sections with large wetted perimeters that in turn indicate hydraulic inefficiency of the gullies.

The tested hydraulic parameters — drainage net, profile, and shape factor — were interpreted as indicating juvenile stages of gully development (termed youthful and early mature). Thus it can be argued that gully development should be recognized in terms of landform evolution, proceeding from young to old age stages. If stages of development could be expressed in terms of erosion rates and sediment yields, a useful tool would be provided for the watershed manager.

When the hydraulic geometry of the gullies was compared with that of rivers, it was suggested that the mature gully stage should be characterized by dynamic equilibrium. The condition of dynamic equilibrium does not represent a true balance between the opposing forces, but includes the capability to adjust to changes in short timespans, and thus regain equilibrium (Heede 1975b). Although some gullies of the Alkali Creek watershed approached this condition, it must be realized that in ephemeral gullies, a mature stage may not be defined by stream equilibrium alone, but may include other aspects of stability such as channel vegetation (Heede 1975a). Invasion of vegetation into the gully is stimulated during dry channel periods.

During the youthful stage, gully processes proceed toward the attainment of dynamic equilibrium, while in the old age stage, a gully loses the characteristics for which it is named, and resembles a river or "normal" stream. Gully development may not end with old age, however. Environmental changes such as induced by new land use (Nir and Klein 1974) and climatic fluctuation or uplift, may lead to rejuvenation, throwing the gully back into the youthful stage.

The condition of steady state, representing true equilibrium, is a theoretical one and can hardly be conceived to apply to gully systems, with the possible exception of very short timespans. Schumm and Lichty (1965) expressed a similar view when they stated that only certain components of a drainage basin may be in steady state.

We must also recognize that gully development is not necessarily an "orderly" process, proceeding from one condition to the next "advanced" one. Erosion processes accelerate at certain times, and at others apparently stand still. For example, Harris (1959) established four epicycles of erosion during the last 8,000 years for Boxelder Creek in northern Colorado. During the interims, the stream was in dynamic equilibrium most of the time. In a case study on ephemeral gullies, it was demonstrated that flows alter the channel, at times leaving a more stable, at others a very unstable, condition (Heede 1967). The latter internal condition leads to the well-known explosive behavior of geomorphic systems (Thornes 1974). External events, however, such as flooding in natural streams, may also lead to rapid, drastic changes (Schumm and Lichty 1963).

Objectives in Gully Control

Main Processes of Gully Erosion as Related to Control

The mechanics of gully erosion can be reduced to two main processes: downcutting and headcutting. Downcutting of the gully bottom leads to gully deepening and widening. Headcutting extends the channel into ungullied headwater areas, and increases the stream net and its density by developing tributaries. Thus, effective gully control must stabilize both the channel gradient and channel headcuts.

Long-Term Objective of Controls — Vegetation

In gully control, it is of benefit to recognize long-and short-term objectives because often it is very difficult or impossible to reach the long-term goal — vegetation — directly; gully conditions must be altered first. Required alterations are the immediate objectives.

Where an effective vegetation cover will grow, gradients may be controlled by the establishment of plants without supplemental mechanical measures. Only rarely can vegetation alone stabilize headcuts, however, because of the concentrated forces of flow at these locations. The most effective cover in gullies is characterized by great plant density, deep and dense root systems, and low plant height. Long, flexible plants, on the other hand, such as certain tall grasses, lie down on the gully bottom under impact of flow. They provide a smooth interface between flow and original bed, and may substantially increase flow velocities. These higher velocities may endanger meandering gully banks and, in spite of bottom protection, widen the gully. Trees, especially if grown beyond sapling stage, may restrict the flow and cause diversion against the bank. Where such restrictions are concentrated, the flows may leave the gully. This is very undesirable because, in many cases, new gullies develop and new headcuts form where the flow reenters the original channel.

Engineers' Measures — An Aid to Vegetation Recovery

If growing conditions do not permit the direct establishment of vegetation (due to climatic or site restrictions, or to severity of gully erosion), engineering measures will be required (Heede 1968b). These measures are nearly always required at the critical locations where channel changes invariably take place. Examples are nickpoints on the gully bed, headcuts, and gully reaches close to the gully mouth where deepening, widening, and deposition alternate frequently with different flows. Nickpoints signify longitudinal gradient changes; a gentler gradient is being extended toward headwaters by headcutting on the bed. Normally, critical locations are easily definable since the active stage of erosion at these sites leaves bed and banks in a raw, disturbed condition.

The designer must keep in mind that well-established vegetation perpetuates itself and thus represents a permanent type of control. In contrast, engineering measures always require some degree of maintenance. Because maintenance costs time and money, projects should be planned so that maintenance is not required indefinitely.

An effective engineering design must help establish and rehabilitate vegetation. Revegetation of a site can be aided in different ways. If the gully gradient is stabilized, vegetation can become established on the bed. Stabilized gully bottoms will make possible the stabilization of banks, since the toe of the gully side slopes is at rest. This process can be speeded up mechanically by sloughing gully banks where steep banks would prevent vegetation establishment. Banks should be sloughed only after the bottom is stable, however.

Vegetation rehabilitation is also speeded if large and deep deposits of sediment accumulate in the gully above engineering works. Such alluvial deposits make excellent aquifers, increase channel storage capacity, decrease channel gradients, and thus, decrease peak flows. Channel deposits may also raise the water table on the land outside the gully. They may reactivate dried-up springs, or may convert ephemeral springs to perennial flow. All these results create conditions much more favorable to plant growth than those existing before control.

Watershed Restoration Aids Gully Control Measures

Measures taken outside the channel can also aid revegetation processes in the gully. Improvements on the watershed that (1) increase infiltration and decrease overland flow, and (2) spread instead of concentrate this flow, will benefit gully healing processes. A study on sediment control measures showed that sediment yields were reduced 25 to 60 percent by land treatment and land use adjustments, as surveyed at 15- to 20-year-old flood water retarding structures in the southern Great Plains (Renfro 1972). But when combined land treatment and structural measures were applied, sediment yields were reduced 60 to 75 percent.

Normally, however, gully improvements can be attained quicker within the gully than outside, because of concentration of treatment and availability of higher soil moisture in the defined channel.

Since watershed restoration measures are only supplemental to gully control, some examples will suffice here: seeding and planting with and without land preparation and fertilization; vegetation cover conversions; and engineering works such as reservoirs, water diversions, benches, terraces, trenches, and furrows.

Immediate Objectives of Control

Different types of measures benefit plants in different ways. It is therefore important to clarify the type of help vegetation establishment requires most. Questions should be answered such as: Is the present moisture regime of the gully bottom sufficient to support plants, or should the bottom be raised to increase moisture availability? One must recognize that a continuous, even raising of the bottom is not possible. Due to the processes of sedimentation above check dams, deposits have a wedge-shaped cross section if plotted along the thalweg.

The immediate objectives of a gully treatment must consider other aspects in addition to plant cover. Usually, these considerations involve hydraulics, sedimentations, soils, and sometimes the logistics required for the management of the watershed. For instance, management may call for deposits of maximum possible depth at strategic locations to provide shallow gully crossings. Thus, if sediment catch is a desirable objective, large dams should be built. But if esthetic considerations make check dams undesirable (and watershed logistics and revegetation offer no problems), the gully bottom may be stabilized with dams submerged into the bed, and thus invisible to the casual observer.

These examples illustrate how important it is to clarify the immediate and overall objectives of a planned treatment before deciding on approaches and measures. The objectives determine the measures; the measures, the type of result.

Gully Control Structures and Systems

Types of Porous Check Dams

The most commonly applied engineering measure is the check dam. Forces acting on a check dam depend on design and type of construction material. Nonporous dams with no weep holes, such as those built from concrete (Poncet 1963, Heede 1965b, Kronfellner-Kraus 1971), sheet steel, wet masonry, and fiberglass, receive a strong impact from the dynamic and hydrostatic forces of the flow. These forces require strong anchoring of the dam into the gully banks, to which most of the pressure is transmitted. In contrast, porous dams release part of the flow through the structure, and thereby decrease the head of flow over the spillway and the dynamic and hydrostatic forces against the dam. Much less pressure is received at the banks than with nonporous dams. Since gullies generally are eroded from relatively soft soils, it is easier to design effective porous check dams than nonporous ones. Once the catch basin of either porous or nonporous dams is filled by sediment deposits, however, structural stability is less critical because the dam crest has become a new level of the upstream gully floor.

Loose rock can be used in different types of check dams. Dams may be built of loose rock only, or the rock may be reinforced by wire mesh, steel posts, or other materials. The reinforcements may influence rock size requirements. If wire mesh with small openings is used, rocks may be smaller than otherwise required by the design flow.

Some different types of check dams will be described, but the field of check dam design is wide open. Many variations are possible. The torrent-control engineers of Europe have been especially successful with filter or open dams. Most of their designs are for large torrents where stresses on the structures are much greater than those in gullies, generally. Clauzel and Poncet (1963) developed a concrete dam whose spillway is a concrete chute with a steel grid as the chute bottom. This grid acts as a filter for the bedload. Periodic cleaning of the dam is required, however.

Other types of filter dams have vertical grids, or grids installed at an angle to the vertical. Such dams are described by Puglisi (1967), Kronfellner-Kraus (1970), and Fattorelli (1971).

All the torrent control dams are quite sophisticated, and thus costly. Such high costs are often justified in Europe, however, since population densities require the most effective and lasting control measures. These qualities are especially important if the basic geologic instability of the alpine torrents is considered. In contrast, most gullies in the western United States are caused by soil failure, and life and high-cost property are not usually endangered. Simpler, low-cost structures will therefore be preferable. Some of the most effective and inexpensive dams are built mainly from loose rock. They will, therefore, be emphasized in the descriptions that follow.

Loose Rock

The basic design of a loose-rock check dam is illustrated in Fig. 1. If facilities are not availble to use the computer program developed by Heede and Mufich (1974), volumes of excavation and of rocks required in the construction can be calculated from the drawings. Rock volumes can also be obtained from an equation discussed in the section on Equations for Volume Calculations. In a Colorado project, the drawings also served well in the field as construction plans (Heede 1966).

Since loose-rock dams are not reinforced, the angle of rest of the rock should determine the slopes of the dam sides. This angle depends on the type of rock, the weight, size, and shape of the individual rocks, and their size distribution. If the dam sides are constructed at an angle steeper than that of rest, the structure will be unstable and may lose its shape during the first heavy runoff. For the design of check dams, the following rule of thumb can be used: the angle of rest for angular rock corresponds to a slope ratio of 1.25 to 1.00; for round rock, 1.50 to 1.00. Fig. 1 illustrates a dam built from angular loose rock.

Wire-Bound Loose Rock

A wire-bound check dam is identical in shape to that of a loose-rock dam, but the loose rock is enclosed in wire mesh to reinforce the structure. The flexibility within the wire mesh is sufficient to permit adjustments in the structural shape, if the dam sides are not initially sloped to the angle of rest. Therefore, the same rock design criteria are required for a wire-bound dam as for a loose-rock structure.

The wire mesh should: (1) be resistant to corrosion, (2) be of sufficient strength to withstand the pressure exerted by flow and rocks, and (3) have openings not larger than the average rock size in the dam. Wire mesh may not be effective in boulder-strewn gullies supporting flows with heavy, coarse loads.

Single Fence

Single-fence rock check dams (Fig. 2) differ greatly in shape and requirements of construction materials from the loose-rock and wire-bound dams. These structures consist of (1) a wire-mesh fence, fastened to steel fenceposts and strung at right angles across the gully, and (2) a loose-rock fill, piled from upstream against the fence. The rock fill can be constructed at an angle steeper than that of rest for two reasons:

1. The impact of flows will tend to push the individual rock into the fill and against the dam.
2. Sediment deposits will add stability to the fill and will eventually cover it.

The design of this type of check dam should emphasize specifications for the wire mesh, and the setting, spacing, and securing of the steel fenceposts. The wire mesh specifications will be the same as those for the wire-bound dams.

The steel fenceposts should be sufficiently strong to resist the pressure of the rock fill and the flows, and must be driven into the gully bottom and side slopes to a depth that insures their stability in saturated soil. If it is impractical to drive posts to sufficient depths, the stability of the posts should be enhanced by guys. These guys should be anchored to other posts that will be covered and thus held in place by the rock fill.

In general, spacing between the fenceposts should not be more than 1.2 m to prevent excessive pouching (stretching) of the wire mesh. Where conditions do not allow this spacing, a maximum of 1.5 m can be used but the fence must be reinforced by steel posts fastened horizontally between the vertical posts. Excessive pouching of the wire mesh reduces the structural height and impairs the stability of the dam.

Double Fence

The double-fence rock check dam has two wire mesh fences, strung at a distance from each other across the channel (Fig. 3). In this type of dam, a well-graded supply ofrocks is essential, otherwise the relative thinness of the structure would permit rapid throughflow, resulting in water jets. Double-fence dams should only be built if an effective rock gradation can be obtained.

In Colorado, parallel fences were spaced 0.6 m (Heede 1966). Peak flows did not exceed 0.7 m^3/s, and loads consisted mainly of finer material. Dams were no taller than 1.8 m. At many dam sites, maintenance and repairs were required because excessive water jetting through the structures caused bank damage. The percentage of small rock sizes was too low.

When flows of large magnitude, say 2 m^3/s, or gullies on steep hillsides are encountered, the base of the double-fence dam should be wider than the crest. This will add structural stability and increase the length of the flow through the lower part of the dam.

Gabion

A gabion check dam consists of prefabricated wire cages that are filled with loose rock. Individual cages are placed beside and onto each other to obtain the dam shape. Normally, this dam is more esthetically pleasing, but it is more costly than loose-rock or wire-bound rock check dams.

Headcut Control

Headcuts can be stabilized by different types of structures, but all have two important requirements: (1) porosity in order to avoid excessive pressures and thus eliminate the need for large, heavy structural foundations; and (2) some type of inverted filter that leads the seepage gradually from smaller to the larger openings in the structure. Otherwise, the soils will be carried through the control, resulting in erosion. An inverted filter can be obtained if the headcut wall is sloughed to such an angle that material can be placed in layers of increasing particle size, from fine to coarse sand and on to fine and coarse gravel. Good results may also be obtained by use of erosion cloth, a plastic sheet available in two degrees of porosity.

If rock walls reinforced by wire mesh and steel posts are used, site preparation can be minimized. Loose rock can be an effective headcut control (Heede 1966) if the flow through the structure is controlled also. As in loose-rock check dams, the size, shape, and size distribution of the rock are of special importance to the success of the structure. The wall of the headcut must be sloped back so the rock can be placed against it.

If the toe of the rock fill should be eroded away, the fill would be lost. Therefore, stabilization of this toe must be emphasized in the design. A loose-rock dam can be designed to dissipate energy from the chuting flows, and to catch sediment (Fig. 4). Sediment depositions will further stabilize the toe of the rock fill by encouraging vegetation during periods with no or low channel flow.

General Design Criteria

Loose Rock

Loose rock has proved to be a very suitable construction material if used correctly. Often it is found on the land and thus eliminates expenditures for long hauls. Machine and/or hand labor may be used. The quality, shape, size, and size distribution of the rock used in construction of a check dam affect the success and lifespan of the structure.

Obviously, rock that disintegrates rapidly when exposed to water and atmosphere will have a short structural life. Further, if only small rocks are used in a dam, they may be moved by the impact of the first large water flow, and the dam quickly destroyed. In contrast, a check dam constructed of only large rocks that leave large voids in the structure will offer resistance to the flow, but may create water jets through the voids. These jets can be highly destructive if directed toward openings in the bank protection work or other unprotected parts of the channel. Large voids in check dams also prevent the accumulation of sediment above the structures. In general, this accumulation is desirable because it increases the stability of structures and enhances stabilization of the gully.

Large voids will be avoided if the rock is well graded. Well-graded rock will permit some flow through the structure. The majority of the rock should be large enough to resist the flow.

Since reuired size and gradation of rock depend on size of dam and magnitude of flow, strict rules for effective rock gradation cannot be given. The recommendations given below are empirical values derived from gully treatments in the Colorado Rocky Mountains, and should be evaluated accordingly. The designer should use these values only as a guide for his decision.

As a general rule, rock diameters should not be less than 10 cm, and 25 percent of all rocks should fall into the 10- to 14-cm size class. The upper size limit will be determined by the size of the dam; large dams can include larger rock than small ones. Flat and round rock, such as river material, should be avoided. Both types slip out of a structure more easily than broken rocks, which anchor well with each other.

In general, large design peak flows will require larger rock sizes than small flows. As an example, assume that the designed total dam height ranges between 1 and 2 m, where total height is measured from the bottom of the dam to the crest of the freeboard. Type of dam is loose rock without reinforcement. Design peak flow is estimated not to exceed 1 m^3/s. An effective rock gradation would call for a distribution of size classes as follows:

Size	Percent
10–14 cm	25
15–19 cm	20
20–30 cm	25
31–45 cm	30

If, on the other hand, dam height would be increased to 3 m, rock up to 1 m diameter, constituting 15 percent of the volume, could be placed into the base of the dam and the second size class decreased by this portion. If peak flow was estimated not to exceed 0.75 m^3/s, the 31- to 45-cm size class could be eliminated and 55 percent of the volume could be in the 20- to 30-cm class.

Spacing

The location of a check dam will be determined primarily by the required spacing of the structures. Requirements for spacing depend on the gradients of the sediment deposits expected to accumulate above the dams, the effective heights of the dams, the available funds, and the objective of the gully treatment. If, for instance, the objective is to achieve the greatest possible deposition of sediment, high, widely spaced dams would be constructed. On the other hand, if the objective is mainly to stabilize the gully gradient, the spacing would be relatively close and the dams low.

In general, the most efficient and most economical spacing is obtained if a check dam is placed at the upstream toe of the final sediment deposits of the next dam downstream. This ideal spacing can only be estimated, of course, to obtain guidelines for construction plans.

Normally, objectives of gully control require spacings of check dams great enough to allow the full utilization of the sediment-holding capacity of the structures. Determination of this spacing requires definite knowledge of the relationship between the original gradient of the gully channel and that of sediment deposits above check dams placed in the gully.

In Colorado, earth dams were examined for guidance in determining the spacing of dams (Heede 1966). Data indicated that, in gullies of less than 20 percent gradient, the dams would not interfere with sediment catch if their spacing was based on the expected slope of the deposits being 0.7 of the original gully gradient. For gully gradients exceeding 20 percent, expected sediment deposits would have a gradient of 0.5 that of the gully. Heede and Mufich (1973) developed an equation to simplify the calculation of spacing as follows:

$$S = H_E / K\ G \cos \& \qquad (1)$$

where S is the spacing, H_E is effective dam height as measured from gully bottom to spillway crest, G represents the gully gradient as a ratio, & is the angle corresponding to the gully gradient (G = tan &), and K is a constant. The equation is based on the assumption that the gradient of the sediment deposits is (1 – K)G. In the Colorado example, values for K were:

$$K = 0.3 \text{ for } G <= 0.20 \qquad (2)$$
$$K = 0.5 \text{ for } G > 0.20 \qquad (3)$$

The generalized equation (1) can be used by the designer, after the applicable K value has been determined for the treatment area. Works older than 10 years should be inspected for this determination. Fig. 5 illustrates the relationship between dam spacing, height, and gully gradient.

For a given gully, the required number of dams decreases with increasing spacing or increasing effective dam height, and increases with increasing gully gradient. An example for a 600 m gully segment is given in Fig. 6.

Keys

Keying a check dam into the side slopes and bottom of the gully greatly enhances the stability of the structure. Such keying is important in gullies where expected peak flow is large and where soils are highly erosive (such as soils with high sand content). Loose-rock check dams without keys were successfully installed in soils derived from Pikes Peak granite, but estimated peak flows did not exceed 0.2 m^3/s (Heede 1960).

The objective of extending the key into the gully side slopes is to prevent destructive flows of water around the dam and consequent scouring of the banks. Scouring could lead to gaps between dam and bank that would render the structure ineffective. The keys minimize the danger of scouring and tunneling around check dams because the route of seepage is considerably lengthened. As voids in the keys become plugged, the length of the seepage route increases. This increase causes a decrease in the flow velocity of the seepage water and, in turn, a decrease of the erosion energy.

The part of the key placed into the gully bottom is designed to safeguard the check dam against undercutting at the downstream side. Therefore, the base of the key, which constitutes the footing of the dam, must be designed to be below the surface of the apron. This is of particular importance for fence-type and impervious structures because of the greater danger of scouring at the foot of these dams. The water flowing over the spillway forms a chute that creates a main critical area of impact where the hydraulic jump strikes the gully bottom. This location is away from the structure. The sides of loose-rock and wire-bound check dams slope onto the apron, on the other hand, and no freefall of water occurs.

The design of the keys calls for a trench, usually 0.6 m deep and wide, dug across the channel. Where excessive instability is demonstrated by large amounts of loose materials on the lower part of the channel side slopes or by large cracks and fissures in the bank walls, the depth of the trench should be increased to 1.2 or 1.8 m.

Dam construction starts with the filling of the key with loose rock. Then the dam is erected on the rock fill. Rock size distribution in the key should be watched carefully. If voids in the key are large, velocities of flow within the key may lead to washouts of the bank materials. Since the rock of the keys is embedded in the trench and therefore cannot be easily moved, it is advantageous to use smaller materials, such as a mixture with 80 percent smaller than 14 cm.

Height

The effective height of a check dam (H_E) is the elevation of the crest of the spillway above the original gully bottom. The height not only influences structural spacing but also volume of sediment deposits.

Heede and Mufich (1973) developed an equation that relates the volume of sediment deposits to spacing and effective height of dam:

$$V_S = 1/2\, H_E\, S \cos \& \, L_{HE} \qquad (4)$$

where V_S is the sediment volume, S represents the spacing, and L_{HE} is the average length of dam, considered for effective dam height and calculated by the equation:

$$L_{HE} = L_B + (L_U - L_B/2D)\, H_E \qquad (5)$$

where L_B is the bottom width and L_U the bank width of the gully, measured from brink to brink, and D is the depth of the gully. If S in equation (4) is substituted, then

$$V_S = (H_E^2/2KG)\,L_{HE} \qquad (6)$$

where the constant K has the values found to be applicable to the treatment area. Equation (6) indicates that sediment deposits increase as the square of effective dam height (Fig. 7).

For practical purposes, based on the sediment deposit model, the sediment curve in Fig. 7 is valid for treatments in gullies with identical cross sections and gradients ranging from 1 to 30 percent. At this range, the difference is 4.5 percent with smaller deposits on the steeper gradients, a negligible fraction in such estimates. The volume of deposits, compared with that on a 1 percent gradient, decreases by 10 percent on a gradient of 45 percent, if the cross sections are constant. Magnitudes of cross sections, of course, exert strong influences on sediment deposition.

In most cases, dam height will be restricted by one or all of the following criteria: (1) costs, (2) stability, and (3) channel geometry in relation to spillway requirements. Cost relations between different types of rock check dams will be discussed later. Stability of impervious check dams should be calculated where life and/or property would be endangered by failure. Heede (1965b) presented an example for these calculations which can be easily followed. Pervious dams such as rock check dams cannot be easily analyzed for stability, however, because of unknowns such as the porosity of a structure.

Severely tested check dams in Colorado (Heede 1966) had maximum heights as follows: loose-rock and wire-bound dams, 2.2 m; and fence-type dams (thickness of 0.6 m), 1.8 m.

In gullies with small widths and depths but large magnitudes of flow, the effective height of dams may be greatly restricted by the spillway requirements. This restriction may result from the spillway depth necessary to accommodate expected debris-laden flows.

Spillway

Since spillways of rock check dams may be considered broad-crested weirs, the discharge equation for that type of weir is applicable:

$$Q = CLH^{3/2} \qquad (7)$$

where Q = discharge in m^3/s, C = coefficient of the weir, L = effective length of the weir in m, and H = head of flow above the weir crest in m.

The value of C varies. The exact value depends on the roughness as well as the breadth and shape of the weir and the depth of flow. Since in rock check dams, breadth of weir changes within a structure from one spillway side to the other, and shape and roughness of the rocks lining the spillway also change, C would have to be determined experimentally for each dam. This, of course, is not practical and it is recommended, therefore, to use a mean value of 1.65. This value appears reasonable in the light of other inaccuracies that are introduced in calculating the design storm and its expected peak flow. For this reason also, the discharge calculations would not be significantly improved if they were corrected for the velocity of approach above a dam. Such a correction would amount to an increase of 5 percent of the calculated discharge at a head of flow of 0.5 m over a dam 0.75 m high, or 8 percent if the flow had a 0.9 m head.

Most gullies have either trapezoidal, rectangular, or V-shaped cross sections. Heede and Mufich (1973) developed equations for the calculation of spillway dimensions for check dams placed in these gully shapes. In trapezoidal gullies, the equation for length of spillway can be adjusted to prevent the water overfall from hitting the gully side slopes, thus eliminating the need for extensive bank protection. In V-shaped gullies this is not possible, generally. In rectangular ones, adjustment of the equation is not required because the freeboard requirement prevents the water from falling directly on the banks. One equation was established, therefore, for V-shaped and rectangular gullies as follows:

$$H_{SV} = (Q/CL_{AS})^{2/3} \qquad (8)$$

where H_{SV} is spillway depth, the constant C is taken as 1.65, and L_{AS}, the effective length of spillway, was derived from the equation

$$L_{AS} = L_U/D(H_E - f) \qquad (9)$$

in which f is a constant, referring to the length of the freeboard. In gullies with a depth of 1.5 m or less, the f value should not be less than 0.15 m; in gullies deeper than 1.5 m, the minimum value should be at least 0.3 m.

For structural gully control, design storms should be of 25 years magnitude, and, as a minimum, spillways should accommodate the expected peak flow from such a storm. In mountainous watersheds, however, where forests and brushlands often contribute large amounts of debris to the flow, the size and the shape of spillways should be determined by this expected organic material. As a result, required spillway sizes will be much larger than if the flow could be considered alone. Spillways designed with great lengths relative to their depths are very important here. Yet, spillway length can be extended only within limits because a sufficient contraction of the flow over the spillway is needed to form larger depths of flows to float larger loads over the crest. The obstruction of a spillway by debris is undesirable since it may cause the flow to overtop the freeboard of the check dam and lead to its destruction.

The characteristics of the sides of a spillway are also important for the release of debris over the structure. Spillways with perpendicular sides will retain debris much easier than those with sloping sides; in other words, trapezoidal cross sections are preferable to rectangular ones. A trapezoidal shape introduces another benefit by increasing the effective length of the spillway with increasing magnitudes of flow.

The length of the spillway relative to the width of the gully bottom is important for the protection of the channel and the structure. Normally, it is desirable to design spillways with a length not greater than the available gully bottom width so that the waterfall from the dam will strike the gully bottom. There, due to the stilling-basin effects of the dam apron, the turbulence of the flow is better controlled than if the water first strikes against the banks. Splashing of water against the channel side slopes should be kept at a minimum to prevent new erosion. Generally, spillway length will exceed gully bottom width in gullies with V-shaped cross sections, or where large flows of water and debris are expected relative to the available bottom width. In such cases, intensive protection of the gully side slopes below the structures is required.

Equation (8) includes a safety margin, because the effective length of the spillway is calculated with reference to the width of the gully at the elevation of the spillway bottom, instead of that at half the depth of the spillway. At spillway bottom elevation, gullies are generally narrower than at the location of the effective spillway length. This results in somewhat smaller spillway lengths, which will benefit the fit of the spillway into the dam and the gully.

If the spillway sides are sloped 1:1, it follows that in V-shaped and rectangular gullies, the bottom length of the spillway (L_{BSV}) is derived from the equation

$$L_{BSV} = L_{AS} - H_{SV} \qquad (10)$$

and the length between the brinks of the spillway (L_{USV}) is given by the equation

$$L_{USV} = L_{AS} + H_{SV} \qquad (11)$$

In trapezoidal gullies, the effective length of the spillway equals the bottom width of the gully. From the discharge equation for broad-crested weirs, it follows that the depth of spillway (H_S) in these gullies is given by the equation

$$H_S = (Q/CL_B)^{2/3} \qquad (12)$$

in which the coefficient of the weir (C) is taken as 1.65.

Lengths at the bottom (L_{BS}) and between the brinks of the spillway (L_{US}) are calculated by the equations

$$L_{BS} = L_B - H_S \qquad (13)$$

and

$$L_{US} = L_B + H_S \qquad (14)$$

respectively.

Apron

Aprons must be installed on the gully bottom and protective works on the gully side slopes below the check dams, otherwise flows may easily undercut the structures from downstream and destroy them.

Apron length below a loose-rock check dam cannot be calculated without field and laboratory investigations on prototypes. Different structure may have different roughness coefficients of the dam side slope that forms a chute to the flow if tailwater depth is low. Differences in rock gradation may be mainly responsible for the different roughness values.

The design procedures for the loose-rock aprons were therefore simplified and a rule of thumb adopted: the length of the apron was taken as 1.5 times the height of the structure in channels where the gradient did not exceed 15 percent, and 1.75 times where the gradient was steeper than 15 percent. The resulting apron lengths included a sufficient margin of safety to prevent the waterfall from hitting the unprotected gully bottom. The design provided for embedding the apron into the channel floor so that its surface would be roughly level and about 0.3 m below the original bottom elevation.

At the downstream end of the apron, a loose-rock still should be built 0.15 m high, measured from channel bottom elevation to the crest of the still. This end sill creates a pool in which the water will cushion the impact of the waterfall.

The installation of an end sill provides another benefit for the structure. Generally, aprons are endangered by the so-called ground roller that develops where the hydraulic jump of the water hits the gully bottom. These vertical ground rollers of the flow rotate upstream, and where they strike the gully floor, scouring takes place. Thus, if the hydraulic jump is close to the apron, the ground roller may undermine the apron and destroy it (Vanoni and Pollak 1959). The end sill will shift the hydraulic jump farther downstream, and with it the dangerous ground roller. The higher the end sill, the farther downstream the jump will occur. Since data on sediment and flow are not usually available, a uniform height of sill may be used for all structures.

Ephemeral gullies carry frequent flows of small magnitudes. Therefore, it is advisable not to raise the crest of the end sills more than 0.15 to 0.25 m above the gully bottom. End sills, if not submerged by the water, are dams and create waterfalls that may scour the ground below the sill. At higher flows, some tailwater usually exists below a sill and cushions to some extent the impact from the waterfall over the sill.

Where the downstream nature of the gully is such that appreciable depth of tailwater is expected, the installation of end sills is not critically important. The hydraulic jump will strike the water surface and ground rollers will be weak.

Bank Protection

Investigations have shown (Heede 1960) that check dams may be destroyed if flows scour the gully side slopes below the structures and produce a gap between the dam and the bank. Since water below a check dam is turbulent, eddies develop that flow upstream along each gully side slope. These eddies are the cutting forces.

Several types of material are suitable for bank protection. Loose rock is effective, but should be reinforced with wire-mesh fence, secured to steel posts, on all slopes steeper than 1.25 to 1.00. The design should provide for excavation of the side slopes to a depth of about 0.3 m so that the rock can be placed flush with the surrounding side slope surface to increase stability of the protection. Excavation of surface materials also assures that the rock would not be set on vegetation. Banks should be protected for the full length of the apron.

The height of the bank protection depends on the characteristics of channel, flow, and structure. Where gullies have wide bottoms and spillways are designed to shed the water only on the channel floor, the height should equal total dam height at the structure, but can rapidly decrease with distance from the structure. In contrast, where the waterfall from a check dam will strike against the gully banks, the height of the bank protection should not decrease with distance from dam to prevent the water from splashing against unprotected banks.

In gullies with V-shaped cross sections, the height of the bank protection should be equal to the elevation of the upper edges of the freeboards of the dam. In general, the height of the bank protection can decrease with increasing distance from the dam.

Equations for Volume Calculations

After the dam locations have been determined in the field, based on spacing requirements and suitability of the site for a dam, gully cross sections at these locations should be surveyed and plotted. If possible, use the computer program developed by Heede and Mufich (1974) to design the dams. Otherwise the dams must be designed from the plotted gully cross sections. Structural and gully dimensions can be used in equations developed by the above authors.

Loose-Rock and Wire-Bound Dams

The volume equation for the dam proper of loose-rock and wire-bound dams considers either angular or round rock, because the angle of repose varies with rock shape and influences the side slopes of the dam. The generalized equation is

$$V_{LR}^2 = (H_D \ /\tan A_R \ + 0.6 \ H_D) \ L_A \ - V_{SP} \qquad (15)$$

where V_{LR} is the volume of the dam proper, H_D represents dam height, 0.6 is a constant that refers to the breadth of dam, L_A is the average length of the dam, tan A_R is the tangent of the angle of repose of the rock type, and V_{SP} is the volume of the spillway. It is assumed that the angle of repose for angular rock is represented by a slope of 1.25:1.00, corresponding to a tangent of 0.8002; for round rock, the slope is 1.50:1.00 with a tangent of 0.6590. L_A is given by the equation

$$L_A = L_B + (L_U - L_B/2D)H_D \qquad (16)$$

where L_B is the length of dam at the bottom, L_U represents bank to bank width of gully, and D is the depth of the gully. V_{SP} is calculated by the equation

$$V_{SP} = H_S L_{AS} B_A \qquad (17)$$

where H_S is the depth and L_{AS} is the effective length of the spillway; B_A is the breadth of the dam, measured at half the depth of the spillway and derived from the equation

$$B_A = H_S \ /\tan A_R + 0.6 \qquad (18)$$

where 0.6 is the breadth of dam.

Angular rock is preferable to round rock because less is required, and it enhances dam stability.

The equation for volumes of loose-rock and wire-bound loose-rock dams (eq. 15) was simplified by assuming a zero gully gradient. This assumption results in an underestimate of volumes in gullies with steep gradients. To offset this underestimate on gradients larger than 15 percent, 10 percent should be added to the calcualted volume.

If the design peak flow is larger than 0.3 m^3/s, all types of check dams must be keyed into the gully banks and bottom. Under varied conditions in Colorado, it was found that a bottom key of 0.6 m depth and width was sufficient for check dams up to 2 m high. A width of 0.5 m was also adequate for the bank keys. The depth of the keys, however, must be adjusted according to characteristics of the soils. Thus, the equation for the volume of the key is generalized as follows:

$$V_K = (L_A + 2R) \ (0.6H_D + 0.36) - 0.6H_D L_A \qquad (19)$$

where R represents the depth of key and 0.6 m and 0.35 m^2 are constants, referring to depth and width of bottom key and width of bank key, respectively.

In the construction plan, the volume V_K should be kept separate from that of the dam proper because, generally, a finer rock gradation is required for the keys.

Apron and bank protection below the structure are always required at check dams. The equation developed for the volume calculations is:

$$V_A = (cH_D L_B + dH_D^2 \ )0.3 \qquad (20)$$

in which V_A is the rock volume of the apron and bank protection, and c and d are constants whose values depend on gully gradient. For gradients <= 15 percent, c = 1.5 and d = 3.0; for gradients > 15 percent, c = 1.75 and d = 3.5.

The total rock volume required for a loose-rock dam with keys is the sum of equations (15), (19), and (20).

Besides rock, wire mesh and steel fenceposts are used in most of the dams. If dam height is equal to or larger than 1.2 m, reinforcement of the bank protection work by wire mesh and fenceposts will generally be required. The equation for amount of wire mesh and number of posts includes a margin of safety to offset unforeseen additional needs. To assist in construction, dimensions of the mesh are given in length and width. The length measured along the thalweg is

$$M_{LB} = 3.50\ H_D \qquad (21)$$

where M_{LB} is the length of the wire mesh for the bank protection, and 3.50 is a constant. The width of the wire mesh, measured from the apron to the top of the bank protection at the dam, equals the total dam height.

The number of fenceposts is calculated by the equation

$$N_B = 3H_D + 2 \qquad (22)$$

where N_B is the number of fenceposts for the bank protection, rounded up to a whole number divisible by 4, and 2 and 3 are constants, the latter derived from a 1.2 m spacing. Of the total number of posts, half should be 0.75 m taller than the dam; the other half are of dam height.

For wire-bound dams, the length of the wire mesh is taken as that of the dam crest, which includes a safety margin and is calculated by the equation

$$M_L = L_B + (L_U - L_B/D)\ H_D \qquad (23)$$

where M_L is the length of the wire mesh. The width of the mesh, measured parallel to the thalweg, depends not only on dam height but also on rock shape. The equation for the width of the wire mesh is

$$M_w = 2H_D/\tan A_R + 2H_D/\sin A_R + 3 \qquad (24)$$

where M_w is the width and A_R the angle of repose of the rock. For angular rock, this angle is assumed to be 38° 40', corresponding to a dam side slope of 1.25:1.00, and for round rocks 33° 25', representing a slope of 1.50:1.00. The term 3 is a constant, in meter units. Equation (24) provides for an overlapping of the mesh by 1.8 m.

Single-Fence Dams

A zero gully gradient was assumed for calculating rock volume for the dam proper of single-fence dams. This results in overestimates that compensate for simplification of the equation for volume calculation. If the construction plan calls for a dam with a 0.6 m breadth, for ease of calculation, the cross section of the dam parallel to the thalweg is taken as a right triangle with a dam side slope of 1.25:1.00 in the equation:

$$V_{SF} = [H_D^2 /2(0.80020)]L_A - V_{SSF} \qquad (25)$$

where V_{SF} is the rock volume of the dam proper, 2 is constant, and 0.80020 represents the tangent of a slope of 1.25:1.00. V_{SSF} is the volume of the spillway, calculated by the equation

$$V_{SSF} = H_S L_{AS} B_{SF} \qquad (26)$$

where B_{SF} is the breadth of the dam, measured at half the depth of the spillway and given by the equation

$$B_{SF} = H_S/2(0.80020) \qquad (27)$$

The length of wire mesh for a single-fence dam is given by equyation (23), while the width equals dam height. The number of fenceposts is calculated by the equation

$$N_{SF} = L_B/1.2 + (L_U - L_B/1.2D)H_D + 1 \qquad (28)$$

where N_{SF} is the number of posts of the dam proper of a single-fence dam, rounded up to a whole number: 1.2 signifies a distance of 1.2 m between the posts; and 1 is a constant. Of the total number of posts, half are 0.75 m taller than the dam; the other half are dam height.

double-Fence Dams

The equation for rock volume of a double-fence dam with vertical fences, 0.6 m apart, is:

$$V_{DF} = 0.6 H_D L_A - V_{SDF} \qquad (29)$$

where V_{DF} is the volume, 0.6 is a constant, and V_{SDF} is the volume of the spillway, computed by the equation

$$V_{SDF} = 0.6 H_S L_{AS} \qquad (30)$$

where 0.6 represents the standard breadth of the dam, in meters.

The length of wire mesh is given by

$$M_{LD} = 2L_B + (L_U - L_B/D)2H_D \qquad (31)$$

where M_{LD} is the length of the mesh. The width of the wire mesh equals dam height. The number of fenceposts is computed by the equation

$$N_{DF} = L_B/0.6 + (L_U - L_B/0.6D)H_D + 2 \qquad (32)$$

where N_{DF} is the number of posts of the dam proper of a double-fence dam, rounded up to a whole even number, and 0.6 and 2 are constants. The equation is based on a post spacing of 1.2 m. Half of the posts are dam height, while the other half are 0.75 m taller than the dam.

Headcut Control

The volume requirements for a headcut control structure are given by the equation

$$V_{HC} = [D^2 /2(0.33333)]\ [L_U + 3L_B/4] \qquad (33)$$

where V_{HC} is the rock volume, D is the depth of the gully at the headcut, and 0.33333 is the tangent of the angle that refers to a structure with a slope gradient of 3:1. If a slope gradient different from 3:1 is selected, the value of the tangent in the equation should be changed to correspond to that gradient.

Rock Volume Relations Among Dam Types

In the Colorado project (Heede and Mufich 1973), rock volumes required for the various types of check dams were expressed graphically (Fig. 8). If this graph is used for decision-making, it must be recognized that double-fence dams had parallel faces 0.6 m apart. Where double-fence structures with bases wider than the breadth of dam are required, rock volume requirements will be larger. The graph shows that a loose-rock or wire-bound dam with effective height of 1.8 m requires about 3 times more rock than a double-fence dam.

Construction Procedures

Before construction starts, the following design features should be staked and flagged conspicuously:

1. Mark the centerline of the dam and the key trenches, respectively, on each bank. Set the stakes away from the gully edge to protect them during construction.

2. Designate the crest of the spillway by a temporary bench-mark in the gully side slope sufficiently close to be of value for the installation of the dam.

3. Mark the downstream end of the apron.

4. For loose-rock and wire-bound dams, flag the upstream and downstream toes of the dam proper.

Caution is required during excavation to avoid destroying the stakes before the main work of installation begins.

The construction of all dams should start with the excavation for the structural key, the apron, and the bank protection. This very important work can be performed by a backhoe or hand labor. Vegetation and loose material should be cleaned from the site at the same time.

The trenches for the structural keys will usually have a width of 0.6 m, therefore a 0.5-m-wide bucket can be used on the backhoe. If the construction plan calls for motorized equipment, two types of backhoes can be used. One, mounted on a rubber-wheeled vehicle and operating from a turntable, permits the backhoe to rotate 360°. This machine travels rapidly between locations where the ground surfaces are not rough, and works very efficiently in gullies whose side slopes and bottoms can be excavated from one or both channel banks. The other type can be attached to a crawler tractor. This type proves to be advantageous at gullies that are difficult to reach, and with widths and depths so large that the backhoe has to descend into the channel to excavate. In deep gullies with V-shaped cross sections, temporary benches on the side slopes may be necessary. Often, the bench can be constructed by a tractor with blade before the backhoe arrives.

The excavated material should be placed upstream from the dam site in the gully. The excavated trench and apron should then be filled with rock. Since a special graded rock is required for the keys, rock piles for keys must be separate from those used in the apron and dam proper. Excavations can be filled by dumping from a dump truck or by hand labor. During dumping operations, the fill must be checked for voids, which should be eliminated.

If dump trucks are loaded by a bucket loader, some soil may be scooped up along with the rock. Soil is undesirable in a rock structure because of the danger of washouts. To avoid soil additions, use a bucket with a grilled bottom that can be shaken before the truck is loaded. Other devices such as a grilled loading chute would also be appropriate.

Dumping rock into the dam proper has two advantages: The structure will attain greater density, and rocks will be closer to their angle of repose than if placed by hand. Hand labor can never be completely avoided, however, since plugging larger voids and the final dam shape require hand placement. Where gullies are deep and dumping is impractical, rock chutes may be used.

Often, gully control projects are planned to provide employment for numbers of people. This objective can easily be accomplished if sufficient supervision is available for the individual steps in the construction. Special attention is needed at the spillway and freeboard. In loose-rock and wire-bound structures, where the shape of the dam is not outlined by a fence as in the other types, experience shows there is a tendency to construct the spillways smaller than designed.

In wire-bound dams, a commercial, galvanized stock fence, usually about 1.2 m wide, can be used. The stay and line wires should not be less than 12-1/2 gage low-carbon steel, the top and bottom wires 10 gage low-carbon steel, and the openings in the mesh 0.15 m. To connect ends of the fence or to attach the fence to steel posts, a galvanized 12-1/2 gage coil wire is sufficiently strong.

The wire mesh of required length and width should be placed over the gully bottom and side slopes after the trench and apron have been filled with rock. Generally, several widths of mesh will be needed to cover the surface from bank to bank. If several widths are required, they should be wired together with coil wire where they will be covered with rocks. The parts not to be covered should be left unattached to facilitate the fence-stringing operations around the structure.

Before the rock is placed on the wire mesh for the installation of the dam proper, the mesh should be temporarily attached to the gully banks. Otherwise, the wire mesh lying on the gully side slopes will be pushed into the gully bottom by the falling rock and buried. Usually, stakes are used to hold the wire mesh on the banks.

After the dam proper is placed and shaped, the fence can be bound around the structure. Fence stretchers should be applied to pull the upstream ends of the fence material down tightly over the downstream ends, where they will be fastened together with coil wire. Then the bank protection below the dam should be installed.

The installation of single- and double-fence dams begins with the construction of the fences after excavation is completed. Construction drawings should be followed closely here, because the final shape of the dams will be determined by the fences. Conventional steel fenceposts can be used. In some locations, the great height of posts may offer difficulties for the operator of the driving equipment, and scaffolds should be improvised. A pneumatically driven pavement breaker with an attachment designed by Heede (1964) can be used to ease the job of driving. Since relatively great lengths of hose may be attached, this tool may be used in deep gullies and on sites with difficult access.

At single-fence dams, dumping of rock is practical if the gully is not excessively deep or wide. At double-fence structures, hand labor or a backhoe or clamshell will be required. The rock should be placed in layers and each layer inspected for large voids, which should be closed manually by rearranging rocks.

Much time and effort can be saved during construction if a realistic equipment plan is established beforehand. Such a plan requires an intimate knowledge of the cross-sectional dimensions of the gullies and their accessibility to motorized equipment. Pioneer roads that might be needed because of lack of access are not only important for equipment considerations, but will also enter into the cost of the construction.

If equipment is to be used, as a general rule, it appears to be advantageous to use heavier and larger machines if their mobility is adequate. Although hourly costs for heavier machines are usually greater, the total cost for a job is reduced.

With few exceptions, conventional construction equipment is not sufficiently mobile to operate in rough topography without pioneer roads. In watershed rehabilitation projects such as gully control, road construction is undesirable because it disturbs the ground surface and may lead to new erosion. It is therefore desirable to consider crawler-type equipment only.

Cost Relations

Relationships between the installation costs of the four different types of rock check dams described here are based on research in Colorado (Heede 1966). The relationships are expressed by ratios (Fig. 9) to avoid specific dollar comparisons. When considering the cost ratio, one must keep in mind that differential inflation may have offset some finer differences in cost. It is advisable, therefore, to test the cost of individual structures by using material and volume requirements as given by the equations. The cost ratios in Fig. 9 can then be adjusted, if necessary.

In a given gully, for example, a double-fence dam with an effective height of 1.8 m costs only about four times as much as a 0.3 m loose-rock dam, while a wire-bound dam 1.8 m high costs 8.5 times as much. Costs will change with different sizes and gradients of gullies, but the general relationships will not change.

It is obvious that the cost of installing a complete gully treatment increases with gully gradient because the required number of dams increases. Figure 10 indicates there is one effective dam height at which the cost is lowest. In the sample gully, this optimum height for loose-rock dams is about 0.6 m, for single-fence dams 0.7 m, and for double-fence dams 1.1 m. A constant gully cross section was assumed. In reality, of course, gully cross sections usually change between dam sites. The optimum height for lowest treatment costs is not a constant, but changes between gullies, depending on shape and magnitude of the gully cross sections at the dam sites.

Since the cost of the dam is directly proportional to the rock volume, Fig. 10 also expresses the relationship between rock requirement and effective dam height. This means that, in a given gully, there is one dam height at which rock requirements for a treatment are smallest.

A treatment cannot be evaluated on the basis of cost of installation alone, because recognition of benefits is part of the decision-making process. Sediment deposits retained by check dams can be incorporated into a cost ratio that brings one tangible benefit into perspective. Sediment has been cited as the nation's most serious pollutant (Allen and Welch 1971). The sediment-cost ratio increases (treatment is increasingly beneficial) with dam height and decreases with increasing gradient (Fig. 11). The example in Fig. 11 shows that a treatment consisting of loose-rock dams on a 2 percent gradient has a sediment-cost ratio larger than 1.0 for effective dam heights of 0.75 m and above. The large ratio is explained by the fact that a gully with a 2 percent gradient requires only a small number of dams (see Fig. 6), while volumes of sediment deposits do not decrease significantly with number of dams or with gradient.

Since single-fence and double-fence dams cost less than loose-rock and wire-bound loose-rock dams for an effective height greater than 0.3 m, the sediment-cost ratio is more favorable for the fence-type structure. The ratios remain smaller than 1.0 on all gradients larger than 5 percent for treatments with loose-rock and wire-bound loose-rock dams, and on gradients larger than 7 and 9 percent for treatments with single-fence and double-fence dams, respectively.

The importance of sediment-cost ratios in relation to gully gradient and effective dam height becomes apparent in situations where not all gullies of a watershed can be treated. Gullies with the smallest gradient and largest depth, and highest possible fence-type dams should be chosen if other aspects such as access or esthetic value are not dominant.

Other Gully Control Structures and Systems

Nonporous Check Dams

Rock can be used for the construction of wet masonry dams. Limitations in available masonry skills, however, may not permit this approach. A prefabricated concrete dam was designed (Heede 1965b) and a prototype installed in Colorado. It required very little time and no special skills for installation. The capital investment for this dam is larger than for a rock structure, however. A prestressed concrete manufacturer must be available reasonably close to the project area, and the construction sites must be accessible to motorized equipment. Where esthetic considerations and land values are high -- recreational sites and parks, for example -- a prestressed, prefabricated concrete check dam may be the answer.

Check dams may also be built from corrugated sheet steel. For successful application, a pile driver is required to assure proper fit of the sheets. Excavating trenches for the sheets jeopardizes dam stability if the refill is not compacted sufficiently. Quite often, insufficient depth of soil above the bedrock does not permit this dam type.

Earth Check Dams

Earth check dams should be used for gully control only in exceptional cases. Basically, it was the failure of the contruction material, soil, that — in combination with concentrated surface runoff — caused the gully. Gullies with very little flow may be an exception if the emergency spillway safely releases the flow onto the land outside the gully. The released flow should not concentrate, but should spread out on an area stabilized by an effective vegetation cover or by some other type of protection such as a gravel field. Most gullied watersheds do not support areas for safe water discharge.

Standpipes or culverts in earth check dams generally create problems, because of the danger of clogging the pipe or culvert inlet, and the difficult in estimating peak flows. Therefore, additional spillways are required.

If soil is the only dam material available, additional watershed restoration measures (such as vegetation cover improvement work and contour trenches) should be installed to improve soil infiltration rates, to enhance water retention and storage, and thus decrease magnitude and peak of gully flows.

Vegetation-Lined Waterways

With the exception of earth check dams, gully control measures described previously treat the flow where it is — in the gully. In contrast, treatments by waterways take the water out of the gully by changing the topography. Check dams and waterways both modify the regimen of the flow by decreasing the erosive forces of the flow to a level that permits vegetation to grow. In waterways, however, flow is modified compared with the original gully, in two ways (Heede 1968a): (1) lengthening the watercourse results in a gentler bed gradient; and (2) widening the cross section of flow provides very gentle channel side slopes. This latter measure leads to shallow flows with a large wetted perimeter (increase in roughness parameter). Both measures substantially decrease flow velocities, which in turn decrease the erosive forces.

Contrasted with check dam control, waterway projects strive to establish a vegetation cover when land reshaping is finished. Indeed, a quick establishment of an effective vegetation lining is the key to successful waterways. It follows that the prime requisites for a successful application are precipitation, temperature, and fertility of soils, all favorable to plant growth. Other requisites are:

1. Size of gully should not be larger than the available fill volumes;

2. Width of valley bottom must be sufficient for the placement of a waterway with greater length than that of the gully;

3. Depth of soil mantle adequate to permit shaping of the topography; and

4. Depth of topsoil sufficient to permit later spreading on all disturbed areas.

Design criteria or prerequisites in terms of hydraulic geometry are not yet available.

Vegetation-lined waterways require exact construction and therefore close construction supervision, and frequent inspections during the first treatment years. The risk, inherent to nearly all types of erosion control work, is greater for waterways at the beginning of treatment than for check dam systems. To offset this risk, in Colorado 19 percent of the original cost of installation was expended for maintenance, while for the same period of time, only 4 percent was required at check dams (Heede 1968b).

Eight percent less funds were expended per linear meter of gully for construction and maintenance of grassed waterways than for check dams. This cost difference is not significant, especially if the greater involvement in waterway maintenance is recognized. In deciding on the type of gully control, one should consider not only construction costs but also risk of and prerequisites for vegetation-lined waterways.

Summary of Design Criteria and Recommendations

Spacing decreases with increasing gully gradient and increases with effective dam height (see Fig. 5). Number of check dams increases with gully gradient and decreases with increasing effective dam height (see Fig. 6). Expected volumes of sediment deposits increases with effective height (see Fig. 7).

For practical purposes, gully gradients ranging from 1 to 30 percent do not influence volumes of sediment deposits in a treatment. On gradients larger than 30%, sediment catch decreases more distinctly with increasing gradient.

Rock volume requirements are much larger for loose-rock and wire-bound loose-rock dams than for fence-type dams. At effective dam heights larger than 0.6 m, treatments with double-fence dams require smallest amounts of rock (see Fig. 8).

At effective dam heights larger than about 0.5 m, loose-rock and wire-bound loose-rock dams are more expensive than fence-type dams. The difference in cost increases with height (see Fig. 9). Single-fence dams are less expensive than double-fence dams at effective heights up to 1.0 m.

Regardless of gradient, in a given gully, there is one effective dam height for each type of structure at which the cost of treatment is lowest (see Fig. 10). For each type of treatment, rock requirements are smallest at the optimum effective dam heights for least costs (see Fig. 10). The sediment-cost ratio (the value of expected sediment deposits divided by the cost of treatment) increases with effective dam height and decreases with increasing gully gradient (see Fig. 11). At effective dam heights of about 0.6 m and larger, single-fence dams have a more pronounced beneficial sediment-cost ratio than loose-rock or wire-bound loose-rock dams. At effective dam heights of 1.1 m and larger, treatments with double-fence dams have the largest sediment-cost ratios (see Fig. 11).

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Symbols

& = angle corresponding to the gully gradient.

A_R = angle of repose of rock.

B_A = breadth of loose rock or wire-bound loose-rock dams, measured at one-half of the depth of the spillway.

B_{SF} = breadth of single-fence dams, measured at one-half of the depth of the spillway.

C = discharge coefficient, taken at 1.65.

C^1 = constant whose value depends on the watershed configuration.

c = constant whose value changes with groups of gully gradients.

D = depth of gully.

d = constant whose value changes with groups of gully gradients.

f = constant whose value changes with groups of gully gradients.

G = gully gradient in percent.

H = head of flow above weir crest.

H_D = total height of dam.

H = effective height of dam, the elevation of the crest of the spillway above the original gully bottom.

H_S = depth of spillway of a dam installed in a rectangular or trapezoidal gully.

H_{SV} = depth of spillway for a dam installed in a V-shaped gully.

K = constant, referring to the expected sediment gradient.

L = effective length of the weir.

L_A = average length of dam.

L_{AS} = effective length of spillway.

L_B = bottom width of the gully.

L_{BS} = bottom length of the spillway of a dam installed in a rectangular or trapezoidal gully.

L_{BSV} = bottom length of the spillway of a dam installed in a V- shaped gully.

L_{HE} = average length of dam.

L_U = width of the gully between the gully brinks.

L_{US} = length between the brinks of the spillway of a dam installed in a rectangular or trapezoidal gully.

L_{USV} = length between the brinks of the spillway of a dam installed in a V-shaped gully.

M_L = length of the wire mesh of a wire-bound dam.

M_{LB} = length of the wire mesh of the bank protection, measured parallel to the thalweg.

M_{LD} = length of the wire mesh for a double-fence dam.

M_W = width of the wire mesh of a wire-bound dam, measured parallel to the thalweg.

N_B = number of fenceposts of the bank protection work.

N_{DF} = number of fenceposts of the dam proper of a double-fence dam.

N_{SF} = number of fenceposts of the dam proper of a single-fence dam.

Q = rate of the peak flow in m^3 /s, based on the design storm.

R = constant, representing the depth of key.

S = spacing of check dams.

V_A = volume of rock for the apron and bank protection.

V_{HC} = volume of a headcut control structure.

V_{DF} = volume of the dam proper of a double-fence dam.

V_K = volume of the key.

V_{LR} = volume of the dam proper of a loose-rock dam.

V_S = volume of sediment deposits above check dams.

V_{SF} = volume of the dam proper of a single-fence dam.

V_{SP} = volume of the spillway of loose-rock and wire-bound loose- rock dams.

V_{SDF} = volume of the spillway of a double-fence dam.

V_{SSF} = volume of the spillway of a single-fence dam.

w = flow width.

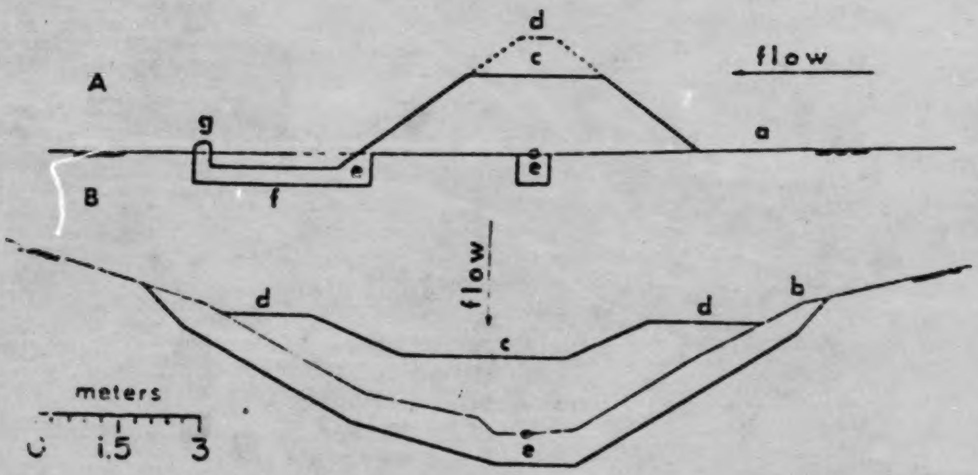
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Figure 1. Construction plans for a loose-rock check dam.
A = Section of the dam parallel to the centerline of the gully.
B = Section of the dam at the cross section of the gully. a = original gully bottom; b = original gully cross section; c = spillway; d = crest of freeboard; e = excavation for apron; g = end sill.

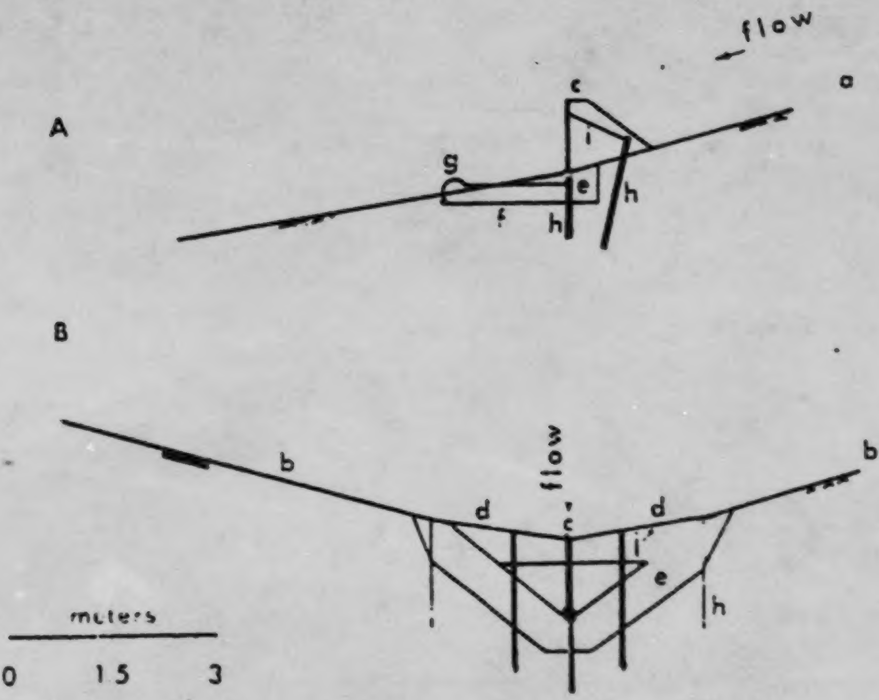
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Figure 2. Construction plans for a single-fence rock check dam.
A = Section of the dam parallel to the centerline of the gully.
B = Section of the dam at the cross section of the gully. a = original gully bottom; b = original gully cross section; c = spillway; d = crest of freeboard; e = excavation for key; f = excavation for apron; g = end sill; h = steel fencepost ; k = guys; j = rebar, 13 mm in diameter.

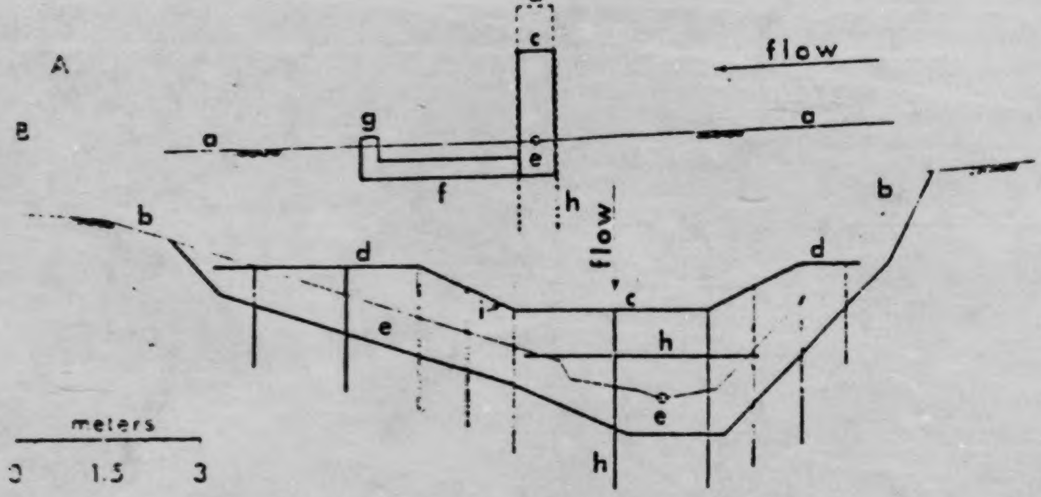

Figure 3. Construction plans for a double-fence rock check dam.
A = Section of the dam parallel to the centerline of the gully.
B = Section of the dam at the cross section of the gully. a = original gully bottom; b = original gully cross section; c = spillway; d = crest of freeboard; e = excavation for key; f = excavation for apron; g = end sill; h = steel fencepost; i = rebar, 13 mm in diameter.

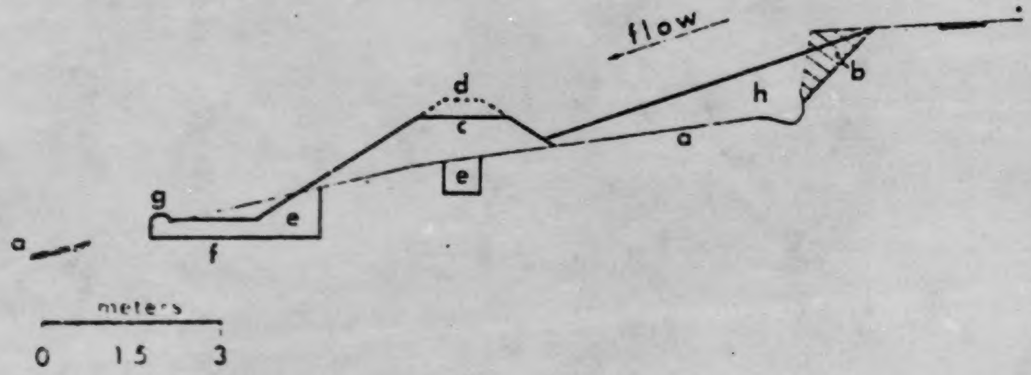

Figure 4. Construction plan for a gully headcut control with a loose-rock check dam. The section of the structure is parallel to the centerline of the gully. a = original gully bottom; b = excavated area of headcut wall; c = spillway; d = crest of freeboard; e = excavation for key; f = excavation for apron; g = end sill; h = rock fill.

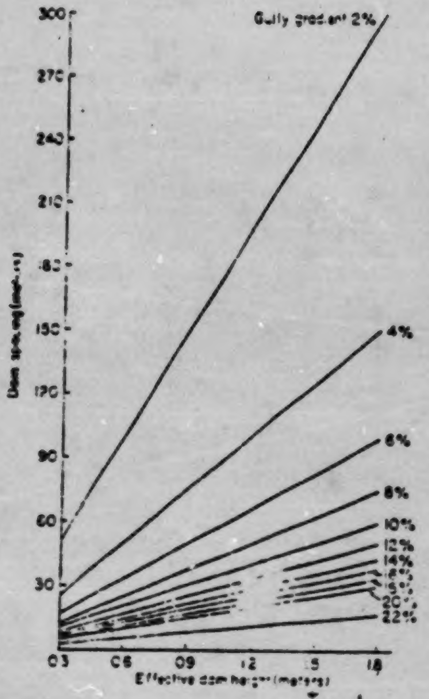

Figure 5. Spacing of check dams, installed in gullies with different gradients, as a function of effective dam height.

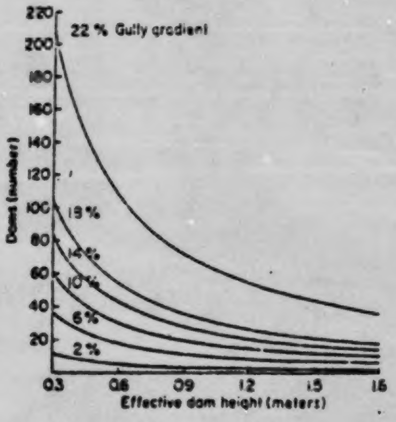

Figure 6. Number of dams required in gullies, 600 m long and with different gradients, as a function of effective dam height.

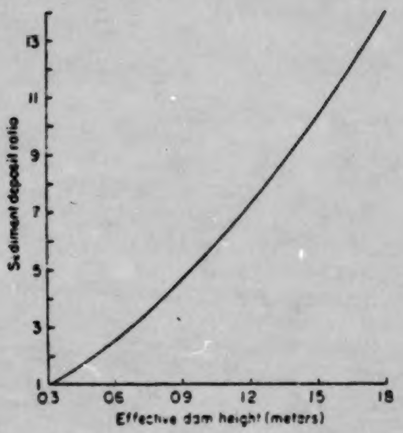

Figure 7. Expected sediment deposits retained by check dam treatment as a function of effective dam height. The sediment deposit ratio relates the volume of sediment deposits to the volume of sediment deposits at effective dam height of 0.3 m. Thus, deposits in a treatment with 1.2 m dams are more than seven times larger than those caught by 0.3 m dams.

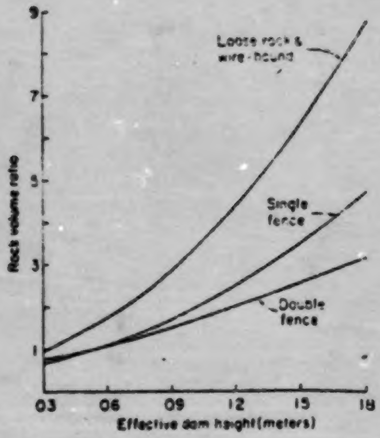

Figure 8. Required volumes of angular rock for four different dam types as a function of effective dam height. The rock volume ratio relates the rock volume to that of a loose-rock dam 0.3 m high.

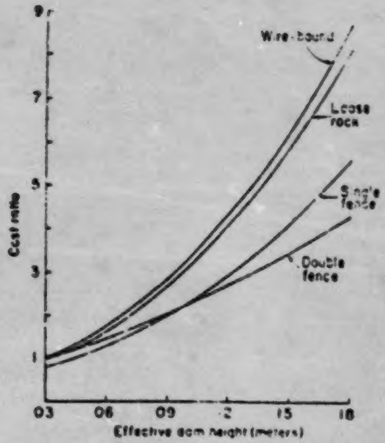

Figure 9. Installation cost of four different types of check dams as a function of effective dam height. The cost ratio is the cost of a dam related to the cost of a loose-rock dam, 0.3 m high, built with angular rock.

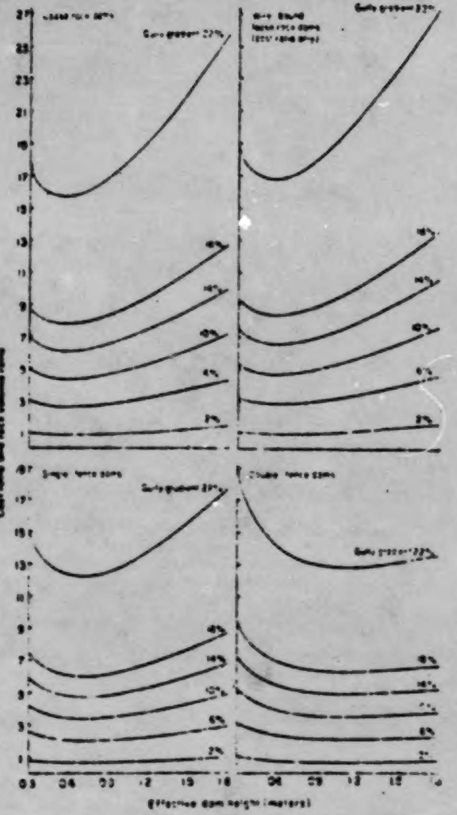

Figure 10. Relative cost of installation of check-dam treatments and relative angular rock volume requirements in gullies with different gradients as a function of effective dam height. The cost and rock volume ratios relate the cost and rock volume of a treatment to those of a treatment with loose-rock dams 0.3 m high installed on a 2 percent gradient.

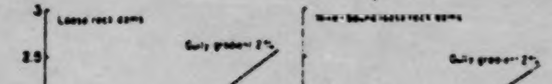

Figure 11. The sediment-cost ratio relates the value of the expected sediment deposits to the cost of treatment. The graphs show this ratio as a function of effective dam height on gully gradients ranging from 2 to 22 percent. The base cost was taken as $20/cubic meter of angular rock dam; the value of 1 cubic meter of sediment deposits was assumed to be one-

Inventory and Evaluation of Rangeland

L. Smith

Introduction

Purpose of Range Inventory

Any resource manager needs information on which to base planning and make management decisions. Such information includes data on climate, soils, geology, topography, animal populations, hydrology, location of natural water, and cultural features such as fences, roads, wells, land ownership status, etc. The range specialist may collect this information himself or rely on collaboration of specialists in various areas. The range specialist usually has primary responsibility for evaluating the status of the vegetation and degree of soil protection on the range. This involves measuring the kind and/or amount of vegetation and soil cover to document changes over time or to make comparisons between areas managed in different ways. The information may be used for such purposes as determining carrying capacity for livestock, estimating range condition, evaluating reseeding or brush control projects, describing patterns of distribution of grazing animals and many other purposes.

Problems of Range Inventory

Many of the principles and techniques used in range inventory are identical or similar to those used in other fields of agriculture such as forestry and agronomy. However there are two main considerations which make range inventory more difficult than measurement of intensive pastures or productive forests. One is cost. Rangelands are usually less productive on an acre (or hectare) basis than other lands and the areas involved are often large, remote and difficult of access. Because of their low productivity the costs of inventory per acre must be kept low.

The second, and most important, problem is variability. Rangelands typically are composed of native plant communities composed of a great variety of species. These species vary widely in growth habit (annual-perennial, bunchgrass-sodformer, herbaceous-shrubby, tall-prostrate, etc.) and in seasonal growth pattern. Measurement techniques which work well on some species are poorly suited or impossible to use on others. Results may differ greatly if measurements are made at different seasons of the year. Another source of variability is due to the variety of soils, elevations, topographic position, slopes and exposures often found within a fairly small area. These lead to differences in species composition and production. Even where these factors are relatively uniform vegetation is often very "patchy" in occurrence due to plant competition and reproductive method. Another important source of variability is caused by high variation in rainfall within short distances and high year-to-year variation typical of rangelands. This means that measurements collected in one place may not apply even a short distance away and it may be necessary to collect data for several years in succession to appropriate a "normal" situation. Finally, variability may be introduced by differing historical use by grazing animals.

Therefore the range manager must continually seek to control variability to the extent possible in his measurement techniques and be continually aware of the variability in his data when making interpretations of it.

There are no simple or standard solutions to the problems of evaluating vegetation especially on rangelands. Different kinds of information are needed in different situations and the type or variability of vegetation may determine the appropriate techniques to be used. Careful thought, especially when embarking on large scale or long-term projects, should be given to the following questions:

1. What attributes of vegetation or soil are most likely to give the information required for decision making and how will the data be interpreted, i.e. What do I really need to know and what must I measure to find out the answer?

2. What are the possible techniques that can be used, modified or developed to give reliable and interpretable results for the kind of vegetation involved?

3. What are the possibilities for controlling variability to increase sampling efficiency?

4. How precisely must attributes be measured to detect the differences expected in time or space?

5. Is an absolute measure needed, or will a relative difference (e.g. trend over time) be just as useful?

6. What kind of preliminary testing and training is necessary to insure that the methods used give repeatable and unbiased results?

Sampling and Measurements

Accuracy and Precision

In any natural resource inventory it is usually impossible or impractical to measure the entire resource. Therefore a sample is taken to represent the whole population. There are two aspects of this sample which are of concern: accuracy and precision.

Accuracy refers to how nearly the sample value approaches the true value for the population, i.e. is it a truly representative sample or is it biased in some way? There are several ways an inaccurate or biased sample may result. Malfunctioning or improperly used equipment may give a bias. For instance, scales that are not properly adjusted may consistently read high or low. Another possibility is technique or personal bias of the data collector. Another is that the sample was not selected properly. For example if all samples were taken near roads the results may not apply to the whole area since roads may tend to avoid steeper or rockier areas. Every effort must be made to eliminate bias or at least to recognize when unavoidable bias exists. Unfortunately, it is usually not possible to measure the amount of bias since the true population value is usually not known.

Precision refers to the repeatability of the measurement. Precision is determined mainly by the natural variability in the material being measured, consistency in technique of the data collector and capability of the equipment used. Precision can be improved by controlling variation in the sampling, improving the technique or equipment used or just by taking more samples. Statistical analysis can be used to estimate precision. A sample may be precise but inaccurate or accurate and imprecise.

Compatibility of Measurements

There are two kinds of error in measurements: absolute error and relative error. Absolute error is expressed in units of measurement, e.g. grams, degrees, while relative error is expressed in percent. If a scale is graduated in one gram increments then it can only be read to the nearest gram, i.e. a weight recorded as 10g may actually be anywhere from 9.5 to 10.5. The absolute error in this case is ± .5g. The relative error is .5g/10g = ± 5%. If the object weighs 100g the absolute error remains the same, ± .5g, but the relative error is now .5g/100g = .5%, a much more precise measurement. Thus, it is important to match the precison of equipment to the precision of measurement required.

Whenever two different kinds of measurements are combined by multiplying or dividing it is important that the relative precision of each be approximately the same. The relative precision of the result is only as good as the least precise component. For example, if you wished to estimate the kilos of crude protein per hectare you need to measure the kilos of plant material per hectare and multiply it times the percent of crude protein in the material. If crude protein content may be measured in the lab to a precision of ± 2% of the average value, but plant material per hectare is only measured to ± 30% of the mean value, then the result will also only have a precision of about ± 30%. Therefore it would be foolish to spend any time or money trying to improve the precision of the crude protein analysis because it will have little effect on the final outcome. Rather, more effort should be put into improving the estimate of total plant material per hectare.

Sampling Design

Basically there are three ways of locating samples in the field: selected, systematic and random. Selected samples are chosen to be representative of an area or situation. For example a permanent plot to measure change in range condition might be located in a key area - one that represents what is happening over the whole area. How well the sample location represents the average situation is a matter of professional judgment. No statistical inference can be made about the whole population but trends over time can be treated statistically.

Systematic sampling involves location of samples in a predetermined regular pattern over the entire area of interest. In this way the sample is representative (or unbiased) but normal statistical analysis cannot be legitimately used, although sometimes it is.

Random sampling involves location of samples by use of random coordinates or other procedures designed to insure that every possible sample unit in the population has an equal and known probability of being selected. This is a necessary requirement for the use of normal statistics. Due to the difficulty of selecting samples completely at random in a large area, some kind of restricted randomization is often used. For instance 10 random points might be selected and then 10 samples randomly located near each point. This results in some loss of precision in the estimate of the mean compared to 100 samples located completely at random, but the saving in time (cost) usually more than compensates for this.

Stratification

Where sampling a range area it is likely that several different kinds of soil or vegetation types will occur in the sample area. Each of these has different characteristics and may differ in variability contained within each type. In this case it is usually advisable to stratify sampling to improve sampling efficiency, to insure that all strata are included or to insure that the most important types are adequately sampled.

If samples are distributed over an entire survey area randomly or systematically, the number of samples falling into each stratum will be proportional to the relative area of each stratum. This is called proportional allocation. However it is important to remember that the number of sample units necessary to sample at a given level of precision is dependent only on the variability of a population and not on its size or area. For example, suppose one is clipping and weighing forage in quadrats in order to estimate average forage production per hectare on a given soil type. If the variability in weight obtained from one quadrat to the next is small, then relatively few quadrats will be needed to get a precise estimate of production. It makes no difference whether the area of the soil type is 1 ha, 10 ha or 1,000 ha, as long as the variability between quadrats does not increase the same number of quadrats will be needed to get the same precision in estimate of the mean.

Now if proportional allocation is used, the largest stratum will receive the greatest number of sample units. If the variability is the same in all strata, the largest stratum will be sampled more precisely than the smaller ones. For example, if soil A contains 75 ha and soil B 25 ha, then 100 quadrats allocated proportionally will place 75 on soil A and 25 on B. If the variability is the same on both soils, soil A will be sampling three times as precisely as soil B. Therefore in order to get equally precise estimates on both soils 50 quadrats should be allocated to each. If soil B is more variable than soil A then more quadrats should be allocated to B than to A.

Allocation of sample units to strata according to the relative variability of the strata, rather than relative area, B called optimal allocation. It is optimal in the sense that it gives equal sampling precision for all strata and the maximum amount of information from a given level of sampling effort.

Number of Sampling Units Necessary

Sample units are the units in which a population is divided for purposes of selecting samples. If meter-square quadrats are used for sampling forage production then each quadrat is a sample unit and represents a sample from all possible meter-square quadrats in the area. How many are necessary to obtain a given level of precision depends only on the variability among them, as shown by the following equation:

$$n = t^2 s^2 / E^2 ,$$

where n = number of units required, t = value of "t" statistic for desired level of probability, s = standard error, and E is one-half the desired confidence interval around the mean.

If you have an estimate of the variability (S) from previous experience or a preliminary test, you can calculate about how many sampling units (n) you need to estimate the mean within certain limits (E) with a known chance of being wrong (t).

A less sophisticated but effective way to estimate adequate sample size is simply to plot a running mean as sampling progresses. For instance, when clipping quadrats you would average the results of the first two quadrats, clip another and average all three and so on. The means obtained will vary considerably at first but eventually will not change much as you add more quadrats. At this point the sample is adequate to give a good estimate of the true mean.

The variability among sampling units is partly due to inherent variability in the soil or vegetation being sampled and partly due to size, shape or arrangement of sample units. Therefore the objective in sampling is to minimize the difference among sample units by including as much variability as feasible within sample units.

Size of Sample Units

Suppose you were estimating the percent of ground covered by a shrub which averaged 4 sq. m in crown area. Assume the actual percent ground cover is 50%, i.e. the size of the bare areas between plants also averages 4 sq. m. If you were using a square quadrat with an area of 1/10 m^2 what would happen? Most of the quadrats would either land completely in a bare spot or within the crown of a shrub; giving cover values of 0% and 100% respectively. Only a few plots would be located overlapping the edge of the shrub to give intermediate values closer to the real cover percentage. The coefficient of variation is very high meaning a large number of plots would be necessary to estimate cover precisely. In fact, the data obtained in this example are not normally distributed and a valid confidence interval could not be calculated using normal statistics.

Now if the plot size is increased more and more plots will overlap the edge of the shrubs and the proportion of plots with 0% or 100% will decline. If the plots are larger than $4m^2$ then very few plots will have these extreme values. Increasing the plot size has reduced the coefficient of variation and fewer would be required to sample at a given loss of precision. The data have also become normally distributed.

If the cover percentage remained at 50% but the average size of shrubs was only $2m^2$, i.e. there are twice as many of them, then the same number of smaller plots or a lower number of large plots could be used. If the shrubs remained at $4m^2$ but cover was only 10%, then using a $4m^2$ quadrat would still result in a very high proportion of zero values (a skewed distribution) and the plot size should be increased. Thus the plot size should be larger than the average size of bare areas between plants and this is a function of both the size and the number of plants.

The preceeding discussion is based on the assumption that individual plants are randomly or regularly distributed over the sample area. However, plants very commonly grow in patches or clumps. This is called a contagious distribution. In this situation, once the size of plot is large enough to overlap more than one plant, a further increase will increase the coefficient of variation because values for plots located inside dense patches increase more rapidly than those in sparse patches. This process would continue until the plot size is bigger than the average size of patches, just as occurred with individual plants. In this kind of situation, one can either sample the patches separately (stratify) or use a plot bigger than the average size of the patches.

The optimum plot size indicated by vegetation characteristics and statistics must be balanced against costs and errors which may occur. Very large plots can be cumbersome to carry or time consuming to lay out on the ground. Therefore it may be more efficient to use smaller plots and take more of them. It is also more difficult to observe large plots and this may result in errors or bias in collecting data. On the other hand large plots have less border effect for a given area than small plots and thus bias may be reduced.

Experience has shown that it is usually best to use the smallest plots possible which do not result in skewed distributions.

Shape of Sample Units

Shape of the sample unit also affects the variability of the sample, and consequently, the number of sampling units required. Shape and size of sampling units are interrelated.

Go back to the example used for plot size, where shrub cover was 50% and average shrub size was $4m^2$. It was concluded that a square plot of $1/10m^2$ was too small and a square plot of about $4m^2$ was required. Now instead of being square, suppose the $1/10m^2$ plot was 1/100 wide and 10m long. Since the average diameter of shrubs and bare spaces is only about 2m, it is likely that a plot 10m long will intersect several plants and several bare spaces. This means that cover values of 0 or 100% would be rare, the distribution would be near-normal, and coefficient of variation much lower than that obtained by square plots of the same size. Therefore a long narrow plot will sample vegetation more efficiently than a square or circular plot.

There are some disadvantages to the long plots however. It may be more difficult to see the whole plot at once or to collect data from it, leading to errors or increased timer per plot. An important source of bias in using quadrats arises in making decisions whether a plant is inside or outside the plot. This decision has to be made at the edge of the plot. Since long, narrow plots have a greater perimeter per unit area the chance for bias due to edge effect is greater for rectangular plots than for square or circular plots of the same size.

Rectangular plots should always be laid out with the long axis running across the gradient patterns of the vegetation. For example, on a slope the vegetation usually changes more from top to bottom than along the contour. Therefore long narrow plots should be laid out with the long axis running up and down the slope since this will cut across the changes in vegetation and reduce variability from one plot to another.

Permanent or Paired Plots

Often the variability on rangelands is so great that it is impossible to measure attributes precisely enough, within the limits of time and money available, to detect change over time or among treatments. One way to get around this problem is to use permanent or paired plots to measure trends.

If you wished to monitor changes in vegetation over time you could select a number of representative locations and mark them. By going back and re-measuring the same plots you could measure trend over time. If the relative change is consistent on these plots the relative change can be stated with confidence. However the absolute change in the true mean over the whole area cannot be determined with much precision because the total number of plots is too low. The use of permanent plots is not possible of course if the method of sampling influences the results obtained, as it would if destructive sampling were used.

When destructive sampling is used or where different treatments are imposed, paired plots can be used. In this procedure pairs of plots are chosen to be as much alike as possible to start with. Treatment is applied to one of the paired plots and not to the other. If the relative change on each pair of plots is similar the relative effects of the treatment can be expressed with confidence, but again the absolute change in the whole area is not precisely known.

Botanical Analysis

General

Many measurements used in range inventory involve measurement of various attributes of the vegetation. There are many different attributes which can be measured and many different techniques for doing so. Most of the attributes however involve some measure of weight, number or cover and most of the techniques are variations on the use of points, lines, quadrats or plotless methods. Some of the most basic and commonly used are discussed below. First, there are some general considerations which apply to all or most of them.

Range plant communities usually contain a variety of different plant species which may vary in size, spacing or growth habit (shrubs, trees, grasses, cactus, etc.). Because of differences in size, number or spacing optimum number, size or shape of sampling unit may be different for each species. In addition, the interpretation of different attributes may vary among species, as well as the most feasible technique for measuring these attributes. For instance, leaf area has no meaning for cactus; stem diameter of shrubs may be difficult to measure on multiple-stemmed shrubs.

Careful consideration must be given to the most appropriate techniques and how the results will be interpreted. It is necessary to specify the "ground rules" on how the data will be recorded; e.g. Will a plant be measured only if it is rooted inside the plot or if a portion hangs over the plot? Preliminary testing of techniques and training of observers is necessary to assure that data will be free from bias.

Most measurements involving several species can be expressed in either relative or absolute terms. Production of species A can be expressed as kilos/hectare or as a percentage of the total production of all species in the community. The relative measure is called composition. Which way the results are expressed depends partly on how the data are collected and partly on how they are to be interpreted.

If the most desired or useful measurement is very difficult or time consuming to obtain then regression (or double-sampling) techniques are often used. This procedure involves the use of a characteristic which is easy to measure and highly correlated with the desired characteristic to estimate the desired characteristic. For instance if height and cover of grasses is found to be highly correlated to production these characteristics may be used as an index to production or to estimate production by regression equations. Although some error is introduced in making the estimate it is more than offset by the increased number of measurements possible since cover and height are much easier and faster to measure directly than production. It is often better to sacrifice some precision on each measurement in order to obtain a greater number of observations.

Density

Density is the number of plants per unit of area, such as trees/hectare. In some cases density is a useful measurement as, for example, in evaluating seedling establishment and mortality, the effects of brush control, age structure of stands, etc. Two problems are often encountered in measuring or interpreting density:

1. Density is not well correlated with other attributes if the size of the plants varies considerably. Ten trees per hectare may have more biomass, annual production, or area than 1,000 grass plants per hectare.

2. It is difficult to distinguish individual plants of some species. Imagine trying to count the number of bermuda grass plants in a lawn. There is no way to tell where one plant starts and the other stops. In this case the only solution would be to count individual stems.

— Ranking - Density may be simply estimated into classes, e.g. very abundant, abundant, occasional, rare, very rare. The classes may be defined in terms of numbers or in descriptive terms. A qualitative rating of density is called abundance.

— Plots - Density is usually measured by counting the number of plants in quadrats. This is very straightforward if individual plants can be identified. The number and size of plots required for efficient sampling usually varies quite a bit among different species. Since the estimate of density for a given unit of area is independent of plot size, different numbers and/or size of plots can be used for each species without affecting the mean estimate. A good rule of thumb for plot size is that average number of plants/plot should be about four.

— Distance Measures (Plotless) - Plots may be difficult to lay out in shrub or forest type vegetation. For this reason distance measures have been proposed. They are easier to use because no plots are required. These methods are based on the concept that density (plants/unit area) is the reciprocal of mean area (area/plant). Area can be calculated by measuring the dimensions of a square, triangle or other polygon having a plant at each corner. Therefore the mean distance between plants is related to the mean area per plant and density can be calculated from mean area as follows: density = 1/mean area. There are four commonly used methods of distance measures, each differing somewhat in the lengths measured and therefore the calculation of mean area.

1. Closest individual - Sample points are located randomly or along a compass line. At each point the distance to the nearest plant is measured. Mean area = $(2d)^2$, where d = the distance measured.

2. Nearest neighbor - Sample points are located as before. The plant nearest the sample point is identified and the distance measured between that plant and its nearest neighbor. Mean area = $(1.67d)^2$.

3. Random pairs - Sample points located as before. At each point, the observer faces the nearest plant. The distance is measured to the nearest plant on the opposite side of a line running through the sample point perpendicular to the direction the observer is facing. Mean area = $(0.8d)^2$.

4. Point centered quarter method - At each sample point the area around the point is divided into quadrants. The distance to the nearest plant in each quadrant is measured and the four distances averaged. Mean area = $(d)^2$.

All of these methods are based on the assumption that plants are randomly distributed. If they are not, the estimate of density obtained will be biased. If the data are recorded on a species basis the relative density of each species can be calculated whether distribution is random or not.

Frequency

Frequency is the number of quadrats in which a species occurs divided by the total number of quadrats, usually expressed as a percentage. For each quadrat, each species is recorded simply as present or absent. The number of plants of each species is not counted.

Frequency of a species is dependent o the size of quadrat used. As quadrat size increases the chance of finding a given species in any one quadrat also increases. If plants are randomly distributed over an area frequency is related to density; as density increases, so does frequency. If plants are not randomly distributed, i.e. they occur in patches or clumps, then there is no fixed relationship between density and frequency. For example if a sample of 100 meter-square quadrats in taken and one plant occurs in each the density is $1/m^2$ and the frequency is 100%. However if all of the 100 plants occur in one quadrat and nothing in the other 99, the density is still $1/m^2$ but the frequency is 1%.

Very high (>95%) or very low (±5%) frequency is difficult to intepret or analyze because distributions are highly skewed at extreme values. A desirable quadrat size is one which will measure the most species within these limits. A general rule is that if the most frequent species are in the range of 65-85% the quadrat size is about right. Sometimes two or more quadrat sizes must be used in order to get information on an adequate number of species. Frequency percentages measured by different quadrat sizes are not comparable however.

Frequency data are analyzed using statistics based on the binomial distribution since only presence or absence is recorded. The variance is estimated as follows:

$$s^2 = pq/n-1 ,$$

where p = the % frequency, q = 1-p, and n = the number of quadrats. About 200-300 quadrats usually give an adequate sample.

For ease of location, frequency quadrats are sometimes located in transects. About 10 transects with 25 quadrats per transect have been recommended.

The principal advantages of frequency samplint are:

1. Data collection is rapid and objective. The observer only has to know the species and decide if they are in or out of the quadrats.

2. Data is quantitative, subject to statistical analyses.

3. Mor complete information on species is usually obtained since the amount of area looked at is large compared to most other types of sampling.

Disadvantages are:

1. Results obtained depend on quadrat size, therefore data collected with different size quadrats is not easily compared.

2. Frequency is difficult to interpret since it measures both number and dispersion of plants. It is not necessarily correlated with density, cover, or production especially for interspecific comparisons.

3. Frequency is an independent measure for each species. This means that data for each species must be analyzed separately, i.e. a total value for all species has no measuring as it does for cover, density or production.

Cover

Vegetation cover and ground cover are often measured in range inventories because (1) vegetation cover is a good indicator of ecological importance of species in a community since it is related both to size and number of individuals and (2) ground cover gives a good measure of site protection. Also, cover measurement is relatively easy and can be consistently measured.

Vegetation cover is a measure of the area of above-ground vegetation in relation to ground area, usually expressed as percentage. There are several ways it can be approached:

- Leaf area index (LAI) - is the total area of leaves by species measured as a percent of ground area. Both interspecific and intraspecific overlap are included. LAI is widely used in agronomic studies on intensive pastures or forage crops because it is related to phtotsynthetic area (i.e. productivity). On denser vegetation LAI usually exceeds 100%, often reaching 500-1000%. It is less used in sparse range vegetation because leaf area and shading are not usually the limiting factors to production.

- Foliar projection - is a measure of leaf (and sometimes stem) cover which is best thought of as the area of shadow which would be produced on the ground if a strong light shone vertically on the vegetation. Overlap of leaves is ignored, therefore this measure is always less that LAI.

- Canopy area - is the toal area included within the perimeter of the plant canopy, i.e. it ignores both leaf overlap on the same plant and the small holes or discontinuities within the canopy. It would always be greater than foliar projection.

- Basal area or cover - is a measure of stem area at the ground surface (or some standard distance above it). Foresters use basal area extensively because it is easy to measure on trees and rlates well to growth and production. Range managers have found it useful for herbaceous plants, especially bunchgrasses, because it is less dependent on current year's growing conditions and less affected by current utilitzation by grazing animals than canopy cover is. Basal area is harder to measure on multiple-stemmed shrubs and generally less meaningful on shrubs because of their variaole growth forms.

One decision that nearly always has to be made when measuring vegetation cover is how to deal with ovelapping canopies of different species. If cover is being measured to express species composition related to relative ecological importance or forage production, then overlap should usually be included - i.e. total crown cover could exceed 100%. However if an index to soil protectin or rainfall interception is the objective, canopy overlap is generally best ignored. In other words the interest may be more in how much ground is uncovered rather than how much is covered.

Ground cover includes vegetation cover and also the amount of litter, rock, gravel and bare soil. These classes are usually defined so that the total adds to 100%.

Visual Estimation

With experience, cover percentage can be estimated visually either by just walking through the area or by using quadrats. Without careful training considerable personal bias can be introduced. An example of the use of quadrats is Daubenmire's canopy cover method. A number of quadrats, usually .25 to 1m^2 are used. Canopy cover by species is ranked in each quadrat as follows:

Rank	Cover %
1	0-5
2	5-25
3	25-50
4	50-75
5	75-95
6	95-100

Ranks are used because it is much faster to decide if a species falls in a certain class than to estimate the exact cover percentage. After a number of quadrats are taken the ranks are multiplied times the midpoint of the class cover percent (e.g. for rank 1 it is 2-1/2%) and averaged. Unequal cover class sizes are used because this gives more sensitivity to species with very high or very low cover percentages.

Point Methods

If frequency quadrats are reduced in size to a dimensionless point, then the percentage or frequency of hits on a plant is an unbiased measure of cover. Points are used in various ways such as line-points, point-quadrat, or step-point methods.

The point-quadrat or point-frame techniques involve the use of a metal or wooden frame designed to hold metal pins in a vertical or oblique position. Usually there are 10 pins to a frame. The pins are lowered slowly to the ground one by one and it is recorded what the point of the pin touches. It may touch leaves, stems, litter, bare ground, etc. Multiple hits on leaves may be recorded if LAI is to be measured. Each 10-point frame is considered an observation or sampling unit. The use of the frame is only a convenience which allows a more objective placement of the pins than would be possible if they were hand-held. The optimum number of pins used per frame and the distance between them depends on size and spacing of plants (as discussed under size of sampling units). The number of frames (or total points) necessary depends on the variability between frames and the sparseness of the vegetation. Points may be spread out along a tape or line at longer intervals than would be practical using a frame. This is called a line-point transect.

Another variation of the point method is the step-point transect commonly used by range managers. In this case, a point is marked, or a notch cut, on the toe of the shoe. The observer then paces a straight line across the sample area and at regular intervals records hits under the point. A pin may be used or merely a visual sighting.

Point methods are fairly rapid to use and give unbiased and objective data if properly done. Some important advantages and disadvantages are:

1. In sparse vegetation, a very large number of points is required to get good estimates on individual species, e.g. when total cover is only 5%, 1000 points will only give 50 hits on vegetation. This is a small sample to base composition on. On the other hand 100-500 points gives a very reliable estimate of bare ground in sparse vegetation.

2. Point methods are best suited to low-growing vegetation. To record "hits" on tall species requires that the observer project the point upward, which is difficult to do in an unbiased manner.

3. Recording foliar hits on windy days is difficult.

4. Bias is introduced (cover over estimated) as the size of the point is increased.

5. In the step-point procedure, bias may be introduced if the observer deliberately or subconsciously lengthens or shortens his pace or deviates from a straight line to miss obstacles in his path.

One way range managers attempt to improve on the estimates of composition in sparse vegetation is to use the nearest-plant technique. At each point location where no plant is hit, the nearest plant to the point is recorded in a "composition tally" in addition to recording bare ground or whatever else the point hits. Thus the number of observations on plant species composition is increased.

Line Interception

In this method a line of known length is stretched between two stakes. The intersection of plant canopies or basal area is measured by species. The total length of intercept divided by the length of the line is an unbiased estimate of percent cover. Each line (transect) is a sampling unit. For efficient sampling, the length of line is usually greater in sparse vegetation than in dense. Lines of 15-50 m length are usually used on rangelands.

Line interception is particularly useful for canopy cover of low-growing shrubs and basal area of bunchgrasses. Basal area on sod-forming grasses or single stemmed herbs is hard to measure. Density is sometimes measured along the transect by counting all plants within a certain distance of the line.

Other Techniques

There are a variety of other techniques used for cover. Foresters have made extensive use of the "variable plot" or Bitterlich method for basal using a prism or angle-gage. It has had limited use for range vegetation however because the margins of plant canopies are less distinct than tree trunks.

Cover of shrubs or trees is sometimes figured by measuring average canopy area of a number of shrubs and multiplying this times the number per hectare.

Various techniques involving mapping or charting of quadrats have been used. These involve a scale drawing of the outline of each plant on a sheet of paper. This is done with a pantograph or by visual estimated or measured coordinates. These are good methods for recorded changes over time and for plant demographic studies. However charting methods are very time consuming.

Vertical photographs can also be used to record cover. Quantification of data by species is not simple however due to difficulty of identification and distortion in the photographs.

Production (Weight)

Weight of plant material is measured for a variety of reasons. It is a good measure of site productivity and ecological importance of species, it is related to carrying capacity, it may be used as a measure of fuel for controlled burns, etc. The actual techniques of measuring weight are fairly simple, although laborious. The most important considerations are what to measure and when to measure.

First, it is necessary to consider the various components of vegetation that can be measured and the terms used to describe them. Biomass is the total amount of plant and animal material present. Above-ground plant biomass excludes animal material and plant roots. Above-ground plant biomass may be divided into living (or green) biomass and dead (or dry). The dead portion can be separated into standing dead (still attached to the plant) and litter or mulch (detached or fallen material). Standing crop usually refers to the living and dead material still attached to the plant at any given time. Production is the total weight of plant material produced over a period of time, whereas productivity is the rate of production over a specified period of time.

Range managers are usually most interested in measuring weight as an indication of site productivity or of carrying capacity. To measure production in a given season or year, it is necessary to separate the material produced prior to that time and only weigh the current year's growth or current season's growth. For example, on a shrub which was several years old we would measure only the leaves and young stems produced this year, which might be only a small portion of the total standing crop. Even grasses and forbs may still have standing growth produced in earlier periods. In some cases, on evergreen shrubs or cactus, for example, it is very difficult to identify current year's growth. Separation may be done in the field or in the laboratory.

In order to use information on production for estimating animal carrying capacity a distinction must be made between total plant growth and forage production. Forage is that portion

In order to use information on production for estimating animal carrying capacity a distinction must be made between total plant growth and forage production. Forage is that portion of the plant growth which animals can and will eat. The proportion of the total production which is considered forage depends on the palatabilty of the plant or plant part (which depends on the kind of animal and season of use), the proper level of utilization which can be made of the plant, and accessibility of the plant material (e.g. leaves growing too high for an animal to reach cannot be considered forage).

Production is usually measured at the end of the growing season since this is when the peak total production for the year occurs. After this time there is a decrease in plant material present because of decomposition, consumption by insects or wild animals, etc. However, even when plants are growing, these losses occur so that production measured at any one time never represents the true total production for the year. This is especially true where two growing seasons occur in one year or where plant species in the community have very different phenological patterns. The underestimate of total production may be slight or range up to about 50% of the true value.

If the range has been or is being grazed by livestock or other animals when production is measured, then the areas used for measurement must be protected from grazing or the amount of forage eaten estimated and added to the production measured. There are techniques available for measuring utilization which will not be discussed here. Regrowth of plants after grazing is another possible source of error.

Production measured for one year may not indicate the average annual rate of production. On many ranges the production per year varies greatly from one year to another due to weather, especially rainfall. Production in good years may be 2-10 times the production in poor years. Therefore measurement of forage production may not mean much unless repeated over several years or adjusted for growing conditions.

Finally moisture content of plants, especially green portions, varies widely depending on the plant part (leaves, stems, seeds), season of year, current soil moisture and even the time of day. For this reason plant weight is almost always reported on a dry weight basis. This means that samples should be oven dried or air dried before weighing or a subsample taken to determine a moisture correction factor.

Harvest Method

The most straightforward way of measuring production is to clip and weigh in quadrats. Separation of different species or of current vs. old growth may be done in the field or in the lab. On sparse range vegetation it is usually easier in the field. Samples may be weighed moist in the field and subsamples taken for moisture correction or the whole sample taken in and dried before weighing.

Clipping plots is a very time consuming procedure and the high variability of range vegetation often requires a large number of samples for reasonable precision. If the number of samples required is large it may take days or weeks to collect them unless a large crew is available. This may introduce additional error because the vegetation may mature or disappear over the sampling period. Thus anything which can increase the sampling efficiency is justified. One way to increase efficiency is to lower the variability between sampling units. This has already been discussed. Another is to decrease the time spent per sampling unit, even at the expense of some precision on each observation, in order to increase the sample size possible for a given amount of time and money. The following techniques are aimed at the latter alternative.

Weight-Estimate

Weight may be estimated in quadrats rather than clipped. Estimation is much faster than clipping but highly subject to bias or error on the part of the estimator. For this reason, extensive training and rechecking is necessary. Estimation is best done by weight-units. The observer selects a convenient amount of plant material for each kind of plant. This may be several small plants or a portion of a larger plant. He estimates the weight of this unit, then weighs it in the field to check his estimate. This process is continued until the observer can estimate different plants consistently. A good estimator can usually come within 10% fairly consistently. Several days of training may be necessary. Estimates should be rechecked frequently, every day or two, because the weight of plants changes rapidly with moisture content and stage of maturity.

A variation of this technique is to clip total production and estimate the percent composition by weight.

Calibrated Weight-Estimate (Double-Sampling)

This procedure is a variation on the weight estimate which uses a regression equation for correction. The estimator trains in the same way described above, prior to sampling. After training he proceeds to sample by estimating weights. In this case a certain percentage, usually 5-10%, of the quadrats are both estimated then clipped and weighed. After several days of sampling, the data from the quadrats which are both clipped and weighed can be used to calculate a regression equation using the formula $y = a + bx$, where y = clipped weight and x = estimated weight. This equation may then be used to correct the other estimated weights. This method assumes the observer is consistent in his estimates even though he may be consistently high or low. If he is not consistent it does not work. Therefore after the initial training he should not check himself during the period for which the equation is developed and someone else should weigh the plots which are clipped. A separate equation should be used for each species or group of similar species, since, for example, one may overestimate shrubs and underestimate grasses.

Properly used, this procedure can improve sampling efficiency considerably.

Other Indirect Methods

Other regression approaches can be used if a relationship between weight and other easily measured parameters can be established. For example, if there is a relationship of weight with height and basal area of bunchgrasses then a formula can be developed to predict weight from measures of height and basal area. These relationships vary from one plant species to the next and may also vary in different years, different sites, different seasons or different age or vigor of plants. Therefore such equations must be developed or tested for every sampling situation. Unless there is a very large amount of sampling to be done, it may not pay to use these approaches.

Range Classification and Mapping

General

Range inventory and management planning almost always involves the making of maps. These maps serve two main purposes. One is to record the location or status of natural and cultural features which influence the management of the range. Such features include fences, roads, land status, water, elevation, etc. The other is to stratify the area into similar portions based on the potential or current characteristics of the resource itself. This may include soil or vegetation type, rainfall, degree of utilization by livestock, erosion, etc. These can be used as a basis for stratification in sampling, for generalizing or summarizing inventory data, for predicting potentials of and/or limitations on management, etc.

Taxonomic Units and Mapping Units

In order to map something it must first be classified. That is, it must be divided into several classes which can be identified and recognized. This is a taxonomic system and each of the classes in it is a taxonomic unit. For instance, if you are mapping vegetation and decide that you will break it down into (1) coniferous forest (2) deciduous forest (3) tallgrass and (4) shortgrass, then these four classes are the taxonomic units of your classification system. They are the basis upon which you will map.

Mapping units are the areas delineated on a map and given a name or number. A simple mapping unit is one where all or most of the area within the unit is composed of one taxonomic unit. It may have minor inclusions of other taxonomic units within it but these do not usually amount to more than about 10% of the total area. For instance, if you drew a line around an area and called it "coniferous forest", it would contain all or mostly coniferous forest with only minor inclusions of other classes, such as deciduous forest or tallgrass.

It may happen however that two or more taxonomic units are so intermixed that it is impossible to draw a line around an area which is predominantly one or the other. In this case about the best you can do is to map areas with similar proportions or patterns of the different taxonomic units. For instance you might map one area which contained about 60% coniferous forest and 40% deciduous forest, another might have 75% deciduous forest and 25% coniferous forest; still another might have 60% deciduous forest and 40% tallgrass with minor inclusions of shortgrass. These are called complex mapping units. They are patterns of taxonomic units rather than uniform areas of one taxonomic unit.

Whether you can map simple or complex units depends on the scale of the map and the complexity of the pattern of taxonomic units in the area. The more finely divided the different soil or vegetation types and/or the smaller the scale of mapping the more likely it is that complex units will be mapped.

The important point is if mapping units are complex, sampling for inventory purposes should be carried out separately on each taxonomic unit within the mapping unit. This will increase sampling efficiency and make the resulting data much more useful and interpretable. Data collected on each taxonomic unit can be weighted by the estimated area of each taxonomic unit to give an overall average for the mapping unit.

Aerial Photos

Range mapping can be and has been done without aerial photos. The use of aerial photos increases the accuracy and efficiency of field work so greatly that it is foolish to attempt inventory of any sizeable area without them. Aerial photos are available now for almost any area in the world, often several different dates and scales are available. Black and white, natural color or color infra-red photos may be used.

Aerial photos always contain some distortion of scale caused by differences in distance to the lens of the camera. However, unless the photography was very poorly done or elevational differences are great in relation to photo scale, these distortions are not enough to affect accuracy of most range surveys greatly.

The first step is to obtain the photos. Black and white are adequate for most range work. Photos are usually flown in strips with each photo overlapping the next about 60% to allow stereoscopic viewing. The strips overlap 10-20% on the sides.

The second step is to delineate effective mapping areas on the photos. Points about midway in the zone of overlap of adjacent photos are selected and located on each photo. Two or three of these points on each side of the photo are connected with lines. The area within the lines is the area mapped on each photo; when you get to the boundary of the effective area you switch to the adjacent photo. These effective areas make it easier to avoid skipping areas and facilitate transfer of information to maps. Delineating effective area on alternate photos within a strip is usually satisfactory and reduces the number of photos needed in the field.

The third step is to pretype the photos. This should be done under stereo if possible. Many features can be mapped in the office, especially if you know the area well. Pretyping should be erasable so it can be changed if field checking shows it to be in error.

The fourth step is to go to the field and complete the mapping. This may be done directly on the photo (with soft pencil) or on a transparent overlay. Exact locations of sample points, fence corners, benchworks, etc. may be pin-pricked through the photo and identified on the back.

The fifth step is to ink on the completed mapping on the photo or transfer it to a planimetric base map. To determine area or distance on the photo or transfer information to a map you need to know the scale of each photo. This can be determined by measuring the distance between two points both on the ground and on the photo and calculating the ratio between them.

Range Condition

Phil Ogden
Professor of Range Mangement, University of Arizona

Introduction

As researchers and resource managers consider data collection and techniques for management of watersheds to improve soil stability and/or water yield, they are immediately faced with the complexity of the watershed resources with which they must work. These complexities are not only in vegetation, soils, topography, and climate but also in differences in uses such as livestock and wildlife grazing. The watershed manager must recognize that grazing influences differ among soils and vegetation communities on watersheds. An initial step in reducing the soil and vegetation complexity is to identify management units which are sufficiently homogeneous so that research data may be extrapolated from one unit to another and to which similar management techniques apply.

Range Sites

A basic unit of land classification which has been utilized in range evaluation, especially by the U.S. Soil Conservation Service, has been the range site. A range site as defined by the Range Term Glossary Committee (1964) is:

An area of land having a combination of edaphic, climatic, topographic and natural biotic factors that is significantly different from adjacent areas. These environmental areas are considered as units for purposes of discussion, investigation, and management. Changes from one site to another represent significant differences in potential forage production and/or differences in management requirements for proper land use.

> Within a specified precipitation zone, topographical position (bottomland, upland, ridge, etc.), slope, aspect, and soil factors combine to create range sites. Each site has a potential to produce specific plant and animal communities and sediment and water yields within a watershed. Sometimes range sites within the watershed are sufficiently large so that they may be mapped and managed as separate entities, but often they occur in patterns where only complexes of sites can be mapped. Sampling, however, should be accomplished at the site level. It is at the range site level that the researcher and manager can correlate treatments and results and, thus, begin to understand apparently unrelated data. Aerial photography is an excellent aid in identification and delineation of range sites within a watershed.

Range Condition and Trend

Each range site has a potential to grow specific plants with a level of vigor, ground cover, and erosion protection which can be called excellent for the site. This potential, or excellent condition, for each range site can be determined by observing well-managed areas. Range condition is defined as the current status of vegetation and soil compared to the potential for the site. Thus, range condition is excellent, good, fair, or poor depending on characteristics of the site at the present compared to what it is capable of producing.

The concept of range condition requires that some potential characteristics of vegetation and soil be established for each site against which current characteristics can be compared. In the United States, ungrazed portions of sites have often been used to establish the potentials. This has been criticized on the basis that ungrazed conditions are not a reasonablé management goal. The researcher or manager has two ways by which he may avoid this criticism. One way is to define the potential as the vegetation and soil characteristics which can be attained under what is considered good management. The second alternative is to define potential in terms of ecological climax vegetation without livestock grazing but set the management goal for the condition level which maximizes returns and proves stability to the watershed. This later approach is preferred if ungrazed areas can be found as a basis for establishing potential.

Plant species composition (relative abundance of different species in the plant community) is one of the most important characteristics related to range condition. There is a dynamic relationship which exists between soils and plant communities on each range site. As plant communities occupy a range site, they in turn modify the site by changing the soil nutrients, water holding capacity, and other factors. These new conditions enable other plant communities to replace the existing communities on the site. This succession of one plant community replacing another continues until a plant community exists which maintains itself on the site (climax community). Figure 1 represents plant community development on a site with fluctuations created by weather cycles. Note that there is a general development toward a climax plant community (C_n) for the site but periods of dry weather cause fluctuations in this development. Vegetational succession on a site may also be reversed by excessive grazing, fire, plant diseases, or mechanical disturbance of the site (C_p). This will level off (C_p) when the disturbance is removed and development again turns upward. Figure 2 shows the relationship between ecological climax and range condition classes. Correct management decisions require the knowledge of the condition of the vegetation of each site, whether the trend is toward succession or retrogression, and the cause for the current situation, Heady (1973).

Dyksterhuis (1949) developed a quantitative method of evaluating range condition based on plant composition which has been widely used by the U.S. Soil Conservation Service. His method classes plants as decreasers, increasers, and invaders. Decreaser plants are those which decrease in abundance, at least initially, with heavy use. Increaser plants are those which initially replace the decreasers in early stages of heavy grazing use but they also decline in abundance as grazing pressure continues and the grazing load shifts to them. Invaders are not present on a site in excellent condition but they move in when decreasers and increasers no longer fully occupy the site. For evaluation of condition, site locations are selected which are producing what is considered to be the potential vegetation for the site. Guides are established for the range site in this excellent condition, listing the plants as decreasers, increasers, or invaders for the site. Increaser plants are given a maximum percentage composition value at which they would occur (percentage allowable toward condition score) on the site in excellent condition. Table 1 shows a hypothetical guide for a range site. The evaluation of condition in the field is made by estimating plant composition on the site under evaluation and comparing with the guide. Composition must be based on the same criteria as the guide but may be based on cover or weight.

Table I

Range condition guide for a sandy upland range site receiving 300 mm of annual precipitation. Plant composition based on percentage by weight.

Decreasers (Count all of percentage compositon toward condition score)	Increasers (Count only percentage allowable toward condition score)		Invaders (Count none toward the condition score)
		Percentage Allowable	
Species	Species		Species
A	D	30	G
B	E	10	H
C	F	5	

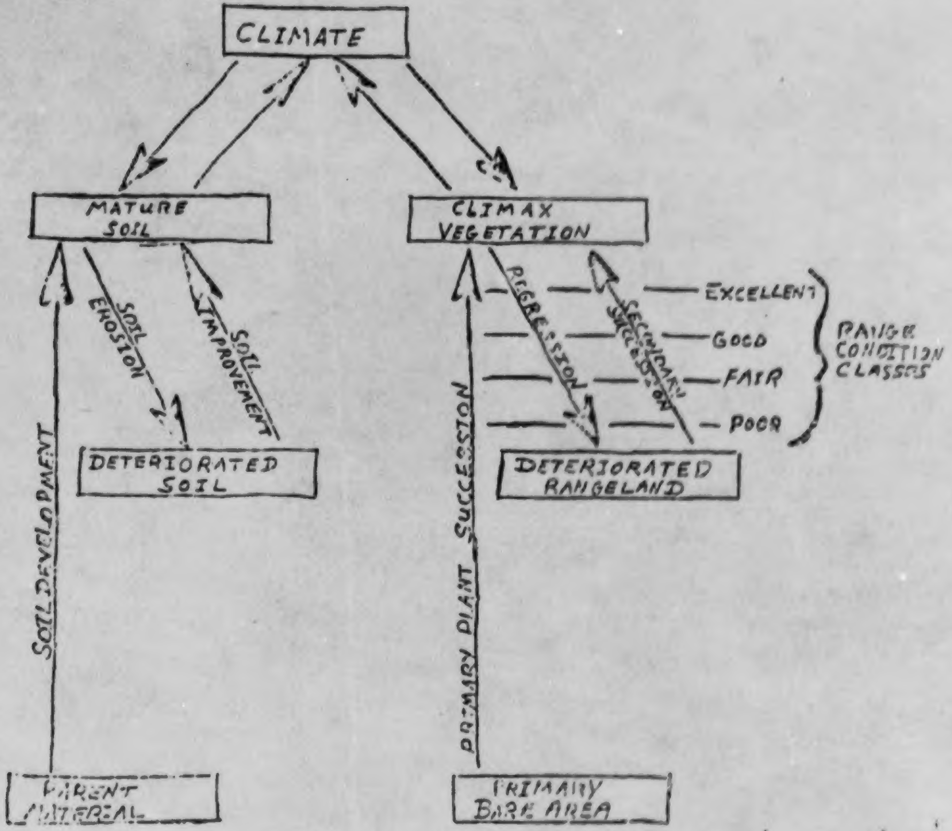
CLIMATE
MATURE SOIL
CLIMAX VEGETATION
SOIL EROSION
SOIL IMPROVEMENT
REGRESSION
SECONDARY SUCCESSION
EXCELLENT
GOOD
FAIR
POOR
RANGE CONDITION CLASSES
DETERIORATED SOIL
DETERIORATED RANGELAND
SOIL DEVELOPMENT
PRIMARY PLANT SUCCESSION
PARENT MATERIAL
PRIMARY BARE AREA

Fig. 1. General plant community succession to a natural climax (C_n) with variations caused by precipitation variability and retrogression to a deteriorated plant community (C_p)

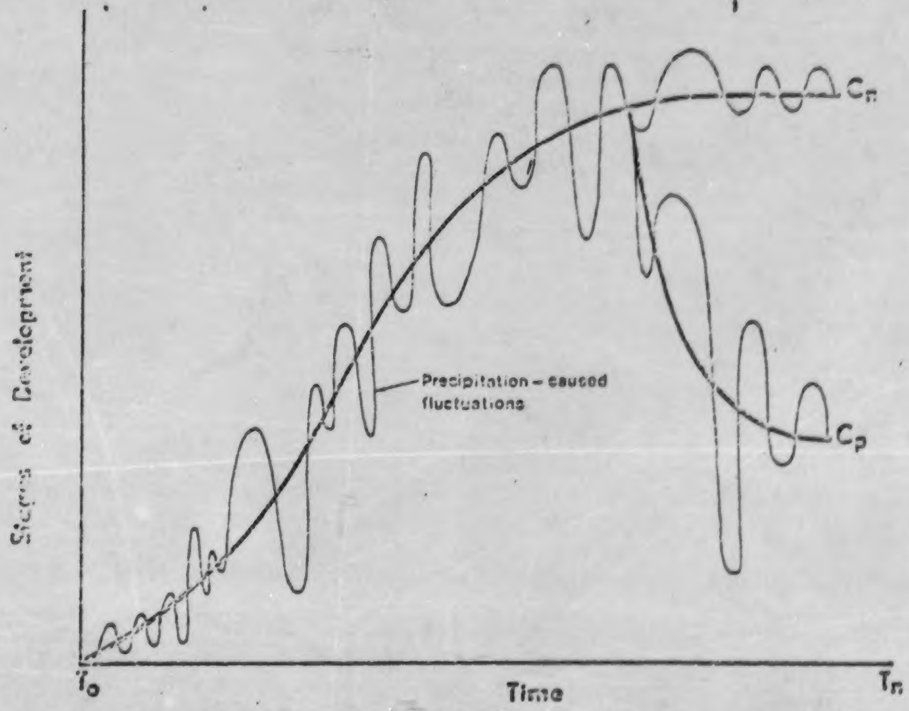

Figure 2. PLANT SUCCESSION, REGRESSION, SOIL DEVELOPMENT AND RANGE CONDITION CLASSES, THOMAS (1970)

Table 2 shows field data for a sandy upland range site and calculation of range condition socre. Scores of 0-25 are poor condition, 26-50 fair, 51-75 good, and 76-100 as excellent condition. Plant cover, litter accumulation, plant vigor, current erosion and other factors may also be utilized to evaluate site condition estimates.

Table II

Field data as percentage plant species composition by weight from sandy upland range site and calculation of a range condition socre.

	Species	Percentage Composition by Weight	Contribution to Condition Score
	A	10	10
	B	10	10
	D	60	30
	F	10	5
	H	10	0
Total		100	55

Condition Score is 55, which is Good condition.

Change in range condition over time is known as range trend. Range trend may be upward (improving), downward (declining), or static. Evaluation of trend helps to monitor use influences on range sites on a watershed.

Plant Growth INfluenced by Grazing

For an understanding of why overgrazing causes vegetation retrogression, it is appropriate to review a few basic plant growth requirements. Each plant growing on the range functions as a converter of solar energy to chemical energy stored in organic compounds. The process by which this is accomplished is photosynthesis which takes place in the green leaves of plants. The chemical energy formed by the plant is utilized by the plant to make root growth and herbage growth, produce seed, and develop winter or drought hardness. Also, it may be stored in roots and stem bases to be used to initiate growth following winter or drought dormancy. Without adequate leaf material left on a plant, it is unable to convert adequate energy to meet its needs for survival. This chemical energy converted by plants is also the source of energy for animal populations which obtain forage from rangelands.

The energy reserves stored in the roots and stem bases of plants is reduced to its lowest levels at the time a plant first initiates growth after a period of winter drought dormancy. Figure 3 shows the accumulation and depletion of carbohydrate reserves in sideoats grama (Bouteloua curtipendula) growing in southern Arizona. Close and continued grazing when reserves are low, so there is no opportunity to replenish reserves, is extremely harmful to plant vigor. After growth has been well started, however, most plants can function effectively and continue to carry on adequate photosynthesis if no more than 50% of their herbage weight is removed.

With close and continued overgrazing, growth is reduced, seeds are not developed, and the plant is reduced in vigor to the extend it is unable to withstand drought or cold or to make regrowth after dormancy. In addition, if grass plants are grazed too closely, the growth buds at the base of the plant are exposed to the temperature extremes of hot in the daytime and cold at night and to extreme drying. Adequate plant material left at the base of plant protects the tender new buds which produce the next crops of herbage.

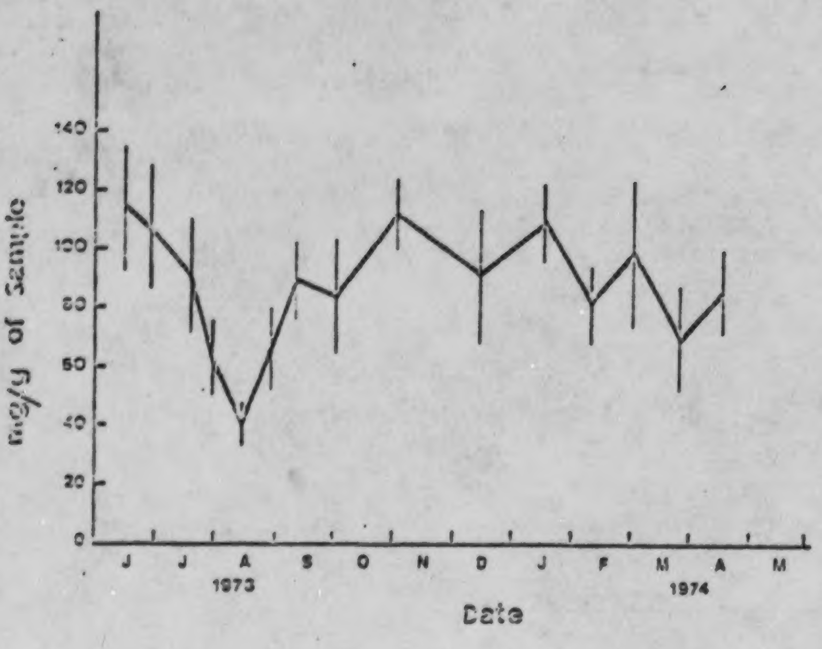

Fig. 3. Carbohydrate reserves as glucose equivalents in roots of sideoats grama collected from The Research Ranch, Elgin, Arizona. 95 percent confidence interval is shown for each sampling date (Sulo 1974).

Individual plants vary greatly as their sensitivity to closeness of grazing and season of grazing. This variability and their different abilities to withstand droughty sites accounts, partly, for the fact that some plants decrease, and some increase in abundance with close grazing. Combined with this is the difference in preference of livestock for different plants. Grazing puts a stress on palatable plants which is not given to unpalatable plants.

Site Characteristics Influenced by Grazing

In addition to the influences of overgrazing on individual plants, there are general influences on the soil and plant community. Probably the greatest influence caused by overgrazing is the reduction in vegetative cover, thus increasing compaction of the soil from rain drop impact and increasing water movement over the soil surface. Removal of vegetation by grazing also may reduce organic matter added to the soil which influences soil structure. Removal of vegetation may also alter the microclimate at the soil level leading to an increase of the soil temperature and, thus, moisture loss by evaporation. Added to these influences are animal influences through soil compaction by trampling and creating trails along which water may flow. The effect of these influences is that overgrazing may create a situation of less available water for plant growth and the retrogression caused by the overgrazing is expressed similarly to, and difficult to distinguish from, a downward trend associated with drought.

The watershed manager, then, must recognize that grazing—whether by domestic livestock or wild herbivores—does influence sites within watersheds and he should work with livestock producers and wildlife managers to develop grazing levels and systems which are of mutual benefit. For most watersheds, there are levels and systems of grazing which are compatible with watershed stability.

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Livestock Grazing Management to Improve Watersheds

Phil R. Ogden
Professor of Range Management, University of Arizona

Introduction

The intensity and amount of rainfall are the major factors influencing runoff and sediment yield from a watershed. The watershed manager cannot control these factors directly, but he can influence their effects by managing the vegetation on the watershed. Livestock exert a major influence on vegetation. Thus, if grazing is a use of the watershed, then watershed management plans must include provisions for grazing management. This paper discusses some of the general considerations which must be the basis for all grazing management programs.

Considerations as a Basis for Grazing Management

The quantity of forage produced, the season or seasons it is produced, and dependability of the production is a first consideration. A cow and calf (considered an an animal unit or roughly 1,000 pounds of live animal weight) require about 900 pounds of range forage per month. This requirement must be met with less than half of the herbage and browse production on each range site, because at least half of the production should be left on the watershed to maintain vigor of plants growing there and provide for ground cover, organic matter return to the soil and maintain a favorable micro-climate on range sites on the watershed.

If the major forage production occurs during a single growing season, then forage must be utilized both to provide forage for livestock and to maintain a protective soil cover on the range throughout the year. Livestock grazing capacity may be limited by the number of animals which can be carried during the dormant periods of vegetation. Herbage and browse production should be managed so that there is adequate provision for watershed protection at the end of dormant periods and prior to major growing seasons. Drought is common in dry climates, and plants may not have enough vigor to recover full production after dry periods, especially if the period extends over more than one season. Stocking, therefore, should be flexible to adjust to a variable forage supply.

The variability of the physiological and morphological growth characteristics of individual plants also influences management. Plants on the same range site may differ in growth characteristics and respond differently to grazing pressure in different seasons. When planning grazing management systems, it is important to know, at least for the major plant species, the periods of new shoot development, carbohydrate depletion and accumulation curves, periods of major new root growth, time of seed production, etc. These characteristics influence the capability of different plants to benefit from periods of rest from grazing and their susceptibility to damage by close grazing at specific seasons.

In addition to the variability in response of individual plants to grazing, there is variability in livestock preference. The preference may be for particular species at any season or there may be a seasonal preference for different species. A major objective of any grazing management system should be to even out the use among plants on the range, so that forage production comes from many plants and not just a few selected species which receive all of the grazing pressure. If one or more major species tend to receive a greater portion of the grazing pressure and are heavily grazed before other species are used, then some management scheme must be used to give these plants a rest. If use cannot be shifted to associated species, the total grazing capacity must be based on the level of use which can be tolerated by the most preferred species.

If topography, vegetation and soils are variable on a watershed, distribution of livestock use over the range may be poor. Livestock tend to use some areas more heavily than others, especially near water, along level bottomlands, ridges, and certain range sites. They may avoid steep slopes, some soils, and dense brush. An attempt to attain uniform livestock use over the range also should be a major objective of any management plan.

The requirements of the livestock must also be considered in any management system. Besides the total intake requirement for forage discussed above, this forage must be of a quality to meet their nutritional needs. We are usually concerned with meeting nutritional requirements in four categories when dealing with range forage: protein, energy, phosphorus, and carotene. All of these nutrients are generally at a satisfactory level when adequate green forage is available. Browse species, however, usually do not contain adequate energy, and dry grass after maturity is low in protein, phosphorus, and carotene. If palatable browse species are present on the range along with grass, nutritional requirements can often be met from range forage alone. If not, some supplementation is necessary. A high nutrition plane is especially important at the time of livestock breeding if a high percentage of the cows are to breed, especially while they are maintaining a calf.

Livestock grazing management programs may also require that additional care be taken of young replacement heifers to provide them with the special attention and feed required for their maximum growth and production. It may also be necessary to maintain bulls separately from the cows for some parts of the year. Cows should be available for observation and for branding and handling calves at time of calving and convenient for rounding up at time of weaning calves and shipping. The livestock grazing management program should not emphasize these livestock care requirements to the detriment of the watershed rsource, but the overall plan, to be effective, must also take into account these livestock handling needs.

Establish Specific Management Objectives

In general, the livestock grazing plan may be directed toward providing maximum livestock production, yet maintaining or improving watershed stability. For any specific watershed, however, the goals should be outlined in more detail, identifying the range sites and even the particular species which are used as the key plants for which management is directed. If a specific area of the watershed is in need of improvement in vegetation cover, specify this as an objective of the grazing management system. Design management to fit the specific objectives.

Implementation of Grazing Management

An inventory of forage available on the watershed is necessary to determine the livestock grazing capacity. Then regulation of livestock numbers so that they are in balance with the forage supply at a level of use which maintains plant vigor and watershed stability is often the major problem which must be solved in implementation of proper grazing management. The level of forage use which will maintain range condition is very dependent on the specific range site, season of use and plants being grazed. A general estimate is to utilize 50% and leave 50%. A proper level of grazing is usually consistent with long-term goals of sustained production for a livestock operation but is not always consistent with short-term economic goals of private livestock producers. Educational programs aimed at showing long-term goals in terms of society needs and presented to livestock producers and the general public are necessary parts of this implementation of proper livestock numbers grazing a range. Ideally, livestock producers should participate in plans for proper stocking if it is to be successful, for they are the persons responsible for the success or failure of grazing management programs. Political and social pressures, however, may be necessary to accomplish proper levels of livestock grazing on watersheds.

Balancing livestock numbers with the forage supply should include procedures to provide flexibility to these numbers to adjust to good and bad forage years with provisions in the management plan for heavy culling and sale of extra animals in drought years. The alternative is to stock at a conservative level so that the watershed is protected even in drought years. This, however, does not utilize forage to optimum levels every year. The provision for flexibility so that numbers can be adjusted upward or downward is a better alternative if it can be accomplished.

Livestock use distribution on ranges usually can be improved by well-planned water developments, because livestock can be attracted to areas where they would not use the forage because of a lack of water. In dry climates, controlling livestock access to water and riding to move livestock from one area to another is a means of regulating areas of livestock concentration. Fencing may be used to regulate where livestock may graze, and trails may be constructed in rough or brushy country to help move livestock from one area to another to obtain more even distribution. Salt also may be used to some extent to attract livestock to areas which would otherwise be little used.

Fencing and water developments may also be utilized to plan a system of grazing so livestock use is regulated at specific seasons to specific areas of the range while resting plant species on other portions of the range. The periods of rest should be designed to enable certain plant species to improve plant vigor by allowing them to make root growth, to seed, replenish carbohydrate reserves, initiate new shoots or to meet a combination of these growth requirements which could not be met under a yearlong grazing period. There are numerous systems of grazing recommended around the world, but any successful system must fit the local conditions if it is to be of any value. Too often grazing systems have been instituted which were not based on local needs and they have not been an improvement over yearlong grazing.

Good livestock husbandry and correct management practices combine to provide efficient conversion of the range forage to marketable protein. The test of an efficient range livestock operation could well be the pounds of range forage consumed to produce a pound of marketable meat. In today's world of protein and energy shortages this is an important contribution of well-managed range lands.

Monitor Results of Grazing Plan

After a grazing plan is put into effect on a watershed, a monitoring program should be established to constantly measure results in terms of range condition on the watershed, on livestock productivity, and other aspects of the watershed which would show influence of the grazing management program. Set up the monitoring program to specifically test whether the objectives of the plan, as initially established, are being met. If the objectives are not being met, determine the causes and make appropriate changes. No management should be static. As more information is gained and objectives change, the plan should be flexible to the changes. But be careful that changes are consistent with the objectives of the watershed management and are not changes to satisfy temporary pressures which may not be in accord with the primary long-range objectives as established.

Vegetation Manipulation on Rangelands

Phil R. Ogden
Professor of Range Management, University of Arizona

Introduction

Any decision to manipulate vegetation on a watershed must be based on an understanding of precipitation patterns, range sites, potential productivity of each range site on which vegetation changes are to be made, and an estimate of successional or retrogressional trends which may result from different management strategies. Previous discussions concerning range sites, range condition, precipitation dependability, and livestock grazing influences provide the basic information necessary to make decisions with regard to vegetation manipulation. Much of the information necessary for making proper decisions must be provided by research.

Manipulating Vegetation with Grazing Animals

With proper grazing management, vegetation condition on sites within a watershed may be improved to provide both improved cover and an increase in desirable plant species. In addition to this general improvement which can be accomplished by good management, there are cases where livestock may be utilized to influence changes in plant species. Cattle, sheep, and goats have forage preference differences and these differences may be further accentuated by seasonal forage preference differences among livestock classes. If research data are available on livestock preference by different seasons and plant growth requirements are known, grazing systems sometimes can be designed to benefit preferred plant species or reduce the vigor of undesirable ones. There are limitations, however. If the undesirable plants are long-lived, such as woody species, and are not palatable to livestock, grazing animals will not eliminate these plants once they have become established. Other methods for changing the kind of vegetation may then be needed.

Manipulating Vegetation with Fire

Plant species are extremely variable as to their response to fire, and there is a seasonal variability in fire damage to plants. For instance, creosotebush (Larrea tridentata) in southern Arizona showed higher mortality from burning in June and July than when burned at other seasons (White 1968). Creosotebush mortality was influenced most by the more intense and longer burning fires in June and July compared to other seasons.

In general, shrubby species are more damaged by fire than herbaceous species, but some shrubs may sprout after being burned so that follow-up treatment may be necessary to obtain control. Research data, or management experience over time, must provide the information on how individual species respond to fire in order to plan efficient use of fire in vegetation manipulation.

A major cost of burning is the herbage which must be conserved for use as fuel rather than as forage. This cost must be included in economic evaluations of burning. Also, any recommended burning treatment must be coordinated with grazing management programs so that fuel is provided for the fire, and forage is provided for livestock. Burning must also be coordinated with precipitation patterns so that burned watershed areas are not devoid of cover when the probability is great for high intensity storms.

Chemical Control of Undesirable Plants

In southern Arizona, diesel oil applied to the base of individual mesquite trees (Prosopis juliflora) killed 90% of the plants (Martin 1957). This is an effective method of shrubby plant control if the shrub species to be controlled is susceptible and if the plants are scattered.

Foliar application of herbicides may also be used to eradicate undesirable species. Low rates of 2,4,5-T sprayed twice in successive years has been effective in controlling mesquite (Cable and Tshirley 1961). Success with foliar herbicides is very seasonal dependent, as the leaves must be at a growth state so that they have adequate surface area, yet have not developed a cuticle layer which reduces absorption of the chemical. For the best plant kill, the herbicide must then be translocated to the roots of the plant. Type of herbicide, rates, and season of application studies are necessary to determine the most effective and economical control conditions. Granular herbicides applied to the ground at the base of plants to be killed are less sensitive to time of application but are dependent on moisture conditions. Effective amounts are dependent on species to be controlled, soil conditions, and moisture. Intensive research programs are needed to make correct recommendations on herbicidal control of undesirable plants on a watershed, Scifres (1977). These research programs should also include monitoring of herbicides in water from a watershed and the effects of the herbicide on plants other than the ones to be controlled.

Chemical control of undesirable plants has the greatest chance of being a useful method of vegetation manipulation when one or more species can be reduced in abundance to allow other, more valuable, native species to increase. If reseeding is necessary because there is a lack of desirable species, then mechanical control which will also provide a seedbed may be the most desirable control method.

Mechanical Treatments to Remove Undesirable Plants

There are numerous methods of mechanical control of undesirable plants which may be utilized to manipulate vegetation. The selection of a method is dependent on species to be removed, soil, labor and equipment available, costs, and the kind of seedbed which is prepared if seeding is to follow mechanical control.

Chopping or grubbing individual plants by hand is effective if plants to be controlled are not too numerous and if relatively cheap labor is available. These methods are not effective in preparing a seedbed if reseeding of the area is necessary.

Cabling or chaining is accomplished by dragging a heavy chain or cable between two crawler-type tractors. This method is good for large trees or shrubs which will either be uprooted by the chain or break off and not sprout. Small, limber shrubs or trees are not well controlled by this method. Soil is disturbed but may not be loosened enough to be a good seedbed on some soils.

Bulldozing individual trees is a method which may be used on nearly all sites except steep slopes. It is best used on large shrubs or small trees. This method may be utilized where plants are scattered or where plants are dense. The cost is greater with denser vegetation.

Rootplowing is an effective control of woody plants. A rootplow can be adjusted for depth to cut below the bud zone. The tilt can be adjusted to lift plants out of the soil and to prepare a good seedbed. For small brush on soils wnich are not too rocky, discing may provide effective control of vegetation and preparation of a seedbed. Pitting may also be accomplished along with, or following plowing, to improve seeding success on certain range sites.

Many mechanical treatment research studies and trials have been conducted throughout the world. The application of results from one area to another depends on characteristics of species to be controlled, soils, and local economic and technical considerations. Any research program on mechanical control treatments, as with any research program, should be based on a critical review of research which has been accomplised in view of possible adaptation to local situations. Then select the most promising methods for trial studies on local range sites.

Reseeding

On areas or sites where high value plant species are in such low numbers that recovery by natural means under proper management is not possible then one should consider reseeding. However, range reseeding is expensive and success is by no means assured, particularly in drier climates. Reseeding success is dependent upon many factors, and research should be aimed at identifying the combination of these factors which contribute to the greatest probability of success for various range sites. There are sites with low rainfall and/or soil conditions which provide a very low chance of successful reseeding. These sites should be identified as well as those sites which can be successfully seeded.

Successful seeding requires that the following conditions be met:

1. A suitable site with soil and precipitation conditions which provide a reasonable probability for success. In general, higher precipitation is required to establish plants on clay soils than on more sandy soils.

2. The plant species to be seeded must be adapted to the site. Selecting adapted ecotypes within a species may also provide an extra measure of success on some sites. Wright and Streetman (1960) discussed methods of selecting for drought tolerance, and Wright has selected seedlings of Lehmann lovegrass (Eragrostis lehmanniana) for drought tolerance which has provided higher seedling survival in southern Arizona trials.

3. Preparation of a seedbed which adequately controls existing vegetation and provides for rapid infiltration of moisture into the soil. A loose, irregular seedbed is often desirable on range seeding operations.

4. Sow adequate seed to insure a successful stand but not to the point of being wasteful. Seeding approximately one million viable seeds per acre is a rough estimate of seeding intensity. For small-seeded species, like Lehmann lovegrass, the seeding rate is less than one pound per acre, and this pound per acre rate increases as seed becomes larger.

5. Provide for proper depth of seed coverage. The smaller the seed, the shallower it should be seeded. Broadcasting of small seed on loose seedbeds is often adequate, but drilling is recommended for large seeds and on crusted seedbeds.

6. Seed at the season when favorable moisture and temperature combine for the longest possible favorable germination and seedling growth period.

7. Provide for protection of seedlings until they have become well established. In very dry sites, this may be for three or more growing seasons.

8. Provide for proper grazing after the reseeded area is grazed again. Reseeding is expensive and can only be justified if it provides returns in forage and for watershed protection over many years.

Vegetation manipulation may be accomplished by many methods or combination of methods. Each method has some advantages and disadvantages for any given situation. The researcher is usually faced with the task of selecting some alternatives which appear best for his area and then conducting trials to determine which are the best for his specific conditions.

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Biomass for Fuelwood and other Energy Applications

Introduction

Forests and associated vegetative communities are among the most important accumulators of energy. Storage of this energy provides a variety of timber, fuels, and organics that are useful for synthetic fibers, plastics, industrial acids, medicines, carbohydrates, and many other substances. Conventional silviculture provides many ways to increase forest growth for timber and to modify forests for wildlife habitats, recreation, and aesthetic values.

Concern for finding new energy sources is increasing interest in converting forests to fuels throughout the world. The phrase "energy forests" implies a special kind of forest management for energy. Unfortunately, past experience has demonstrated that the culture of plantations for timber production requires large investments in fossil fuels. Further, the demand for wood-based energy comes at a time when analyses suggest increased demands for timber and fiber. A number of timber-related industries are making large investments to increase production and are searching the world for opportunities to exploit the remaining natural forests. Further, the people in many countries depend on a rapidly shrinking wood supply for fuel. Clearly, the world faces a variety of competing demands for forest production. Yet, our experience has shown that exploitation of forests can have important ecological, sociological, and economic implications. The problem is how to interrelate the biological potentials for production with the sociological, environmental, and economic values of forests.

Decisions for the rational use of forests are complex because demands for forest benefits are expanding rapidly to include a wide variety of physical goods and nonconsumptive services. Methods are needed to match an increasing variety of benefits with an increasing variety of management without creating insoluble conflicts in actions. Examples of different kinds of management are the maintenance of a place to live for all endemic species; the production of lumber, firewood, food and fiber; the regulation of flows of water and nutrients; and management for recreation, aesthetics, hunting and fishing, and maintenance of living space for man.

For centuries, fuelwood and timber for construction and fiber have been removed from forests. Yet, the biological potentials for production have not been interrelated with studies of the long-term sociological and economic consequences. The increasing cost and scarcity of fossil fuels suggests that forest resources may become a primary, relatively inexpensive source of supply. The question is no longer one of forest exploitation for timber or fuelwood, but a question of the long-term survival of people and civilizations.

Forest Use and Energy Flow

Forests and associated vegetative communities make a major contribution to energy use. Approximately one-sixth of the world's annual fuel supplies are wood fuel and about half of all trees harvested are used for cooking and heating purposes. In countries where excessive deforestation has occurred, such as Nepal and Papua New Guinea, village women and children daily have to walk long distances in search of fuelwood. While forest utilization in such situations is intensive, the energy cost of the daily search is high and wasteful of human resources. Agroforestry in which land-use systems are being developed to provide closer integration between agricultural and forest production seems to offer hope for the future; in India, Egypt and China, it has reached an advanced stage and farmers include trees as one of their crops.

Despite major research efforts mounted over the last few decades, knowledge of the functioning of forest ecosystems unfortunately is incomplete. For a few forests, not necessarily representative of the world's forests, estimates of energy capture as above ground plant net production and of the major pathways of organic turnover have been made. But for most forests, and especially commercial forests, knowledge of productivity is limited to estimates of millable timber.

World maps of global productivity patterns have illustrated the importance of environmental factors and of differences between ecosystem types. Tentative estimates of the earth's primary production indicate that forests and woodlands produce about 45 percent of the annual production of organic matter. The carbon contained in their biomass (estimated as 400-700 x 10^9 tons) is not much less than carbon present as carbon dioxide in the atmosphere (700 x 10^9 tons).

If balance sheets of energy and organic flow for different forest types and vegetative communities are prepared as guidelines for more rational use of forest resources or to assess the potential of forests as a source of photobiological fuels, several different organic and energy pathways need be quantified. In addition to the natural flows of energy into (mainly captured by photosynthesis) and out of (mainly by respiration and decomposition) forest ecosystems, and the resultant changes in the amounts of energy contained in the forest biomass, it is necessary to determine energy removal in the variety of products harvested, the energy required to sustain and harvest the forest, and energy used to transport and process forest products.

The world's annual use of energy is only about one-tenth of the annual photosynthetic storage, so there appears to be considerable potential to harvest plant organic matter for energy. Consideration is being given in some countries to energy forests as a means of capturing solar energy for human use. The advantages of using such an energy source are that it is based on a renewable resource, is less ecologically offensive than some other sources of energy, and is within the capacity of known technology. To achieve high levels of efficiency, such schemes may have to be based on forest monoculture over large areas, mechanical silviculture, and more rapid rotations than formerly. Considerable doubt exists about the validity of such schemes, however. Inevitably, large areas of land are needed and must be set aside against the needs of other rural and urban uses. Intensive forestry can be demanding of labor, capital, water, and fertilizers. The cost of transporting forest produce to processing plants is expensive. Environmental problems arise with the heavy and widespread use of fertilizers and severe effluent disposal problems result from wood hydrolysis processes, and in obtaining petrochyemical substitutes and gaseous fuels from trees. Monocultures and intensively used forests may prove costly to protect against the ravages of fire, pests, or disease organisms, and they have adverse effects on the soil.

Synthetic fuel available for use in internal combustion engines can be produced from cellulose and other plant material via processes such as enzyme hydrolysis of starch and fermentation of organic material to methane and pyrolysis of wood to produce pyrolytic oil. It appears a significant part of the world's liquid fuel might be derived from cellulose by growing trees and other plants specifically for conversion to liquid fuel.

As an example, studies have been conducted to examine the consequences of meeting one-half of Australia's liquid fuel requirements in the year 2000 by producing "energy crops" and converting them to alcohol for use as fuel. In the case of eucalyptus, the cost would be $1.60 (U.S.) per gallon requiring 13 million hectares of land; the comparative figures are $0.80 (U.S.) per gallon and 4.5 million hectares for cassava. Alcohol contains only about 62 percent as much energy as petrol which costs $0.42 (U.S.) per gallon without tax. The availability of land and other resources to grow these energy crops and the social and environmental consequences may present serious practical problems, however.

Energy forestry could be more profitable if the annual yield per hectare could be increased without a disproportionate rise in costs. The main possibilities of improving energy yield appear to be improved management practices including the introduction of trees bred for high photosynthetic efficiency and better utilization of all kinds of forest organic matter.

Various claims have been made by some researchers based on the study of open grown trees that there is a large potential to increase organic production. These claims seem overly optimistic. In considering native forest production, it is essential to think in terms of photosynthesis of the forest as a unit on an area basis.

Studies of production in forest age sequences suggest that the greatest levels of organic production tend to occur relatively early, usually just after the forest canopy closes, when there is the maximum amount of leaf. It seems that, where soil nutrients and water are not limiting, native forest production can equal that of other high producing plant communities provided that the tree species used have a high photosynthetic efficiency, the forest rotation is relatively short, and the initial stocking is high to make full use of the site when the trees are young. Economic production can also be increased by using species which divert a greater proportion of the photosynthate into harvestable wood material. It has also been thought that coppice woodlands are capable of high levels of net production because less photosynthate goes into root production and stem growth from the coppice shoots is rapid after harvesting.

However, the scope to increase organic production by native forest stands is limited since the photosynthetic process is relatively inefficient in capturing incident solar energy. There are also problems of maintaining forest production over several rotations. In Australia, for example, there is evidence of a fall-off in production in second rotation stands although the reasons for this are not fully understood. While energy forests are probably not the only answer to the energy crisis they do provide an opportunity to lessen its impact.

Environmental Consequences

The harvest of forests for wood products and energy, particularly whole-tree harvesting, disturbs the water, air, and soil. Existing knowledge about environmental consequences comes primarily from analyses of the removal of timber from large areas and the clearing of land for agriculture. In general, extractions by people living on or near forests cause little disturbance so long as the number of people is small. However, extraction from large contiguous areas is most destructive.

Frequent harvesting, intensive and repeated cultural treatments (such as cultivation and irrigation) pose dangers of soil erosion, compaction, and nutrient and organic matter depletion. Chemical contamination of the soil can occur following the application of fertilizers and pesticides. And, any or all of these factors may induce detrimental microbiological changes. These intensive forms of forestry are being used in many parts of the world, especially in the tropics. In Latin America, for example, exploitation of patches of forests for agriculture reduces productivity of the land for both food and fuels.

Potentially, energy plantations have problems similar to other forms of agriculture. These problems may often be acute, since energy plantations are typically thought to be appropriate for marginal landscapes unfit for regular agriculture. If the soil is to be artificially created, as in mature agricultural districts, refertilization, recycling of organic matter, and the development of genetically adapted trees must be done by man; this will entail a cost and will require considerable research as well. Generally, people do not know how to fit fertilization, manuring, recycling of organic wastes, and genetically modified trees to forest soils so that the maximum amount of diffuse solar energy is fixed for harvesting.

Energy plantations will affect recreation and scenic values as well as the livelihood for many plants and animals. Plant and animal populations will change depending upon changes in habitats. Wildlife habitat may be impaired by reducing the proportion of most producing and old-growth forests and by frequent disturbance of the forest. Herbivores, insects and diseases may become problems in energy plantations, especially if these are even-aged stands of a single species.

It has been pointed out that, in Indonesia, in situ conservation is a most effective way to prevent the loss of productivity and the loss of genetic materials in native tropical forests. Specifically, solutions to the problems caused by shifting cultivation and poor logging operations are needed. Both of these actions have transformed productive forests into unproductive secondary forests and unproductive grasslands, which total many millions of hectares. In addition, plant and animal communities may be dislocated, soils are frequently degraded, and genetic diversity of native species is often reduced. There is also a risk of actually losing some species by inappropriate use of the forest.

At the recent Eighth World Forestry Congress, many people expressed concerns over the environmental consequences of using forests for energy. These concerns include the lack of ecological basis for the presently used cutting methods, the indiscriminate use of selection and clearcutting methods for regeneration, and the lack of knowledge about species composition, growth, and yield of the second crop. It is already known that certain practices must be implemented, such as minimizing the width of extraction paths, refraining from making unnecessary tractor paths, avoiding excessive wet-weather yarding, and the use of winching techniques to avoid the use of tractors on small hills.

Another important point to be made is that, while rates of wood production in the tropics are roughly equal to that in the temperate zone on a yearly basis, environmental costs may be higher. High environmental costs result from nutrient losses, soil erosion, and increased numbers of parasitic species. Except for specific cases (such as Puerto Rico, where nutrients and water are not limiting), the immediate prospects for energy plantations in Latin America, Africa, and Asia are not thought to be bright.

Over time it is likely that people will become more and more dependent on using woody material for energy and organics. This increased use of woody materials depends, in large part, upon improved technological developments for the culture of woody plants. One of the important challenges is to find ways to direct the flows of diffuse, solar energy through natural and artificial ecosystems in such a way that biological diversity and productivity of the Earth is preserved. In the words of Rene DuBos, "...the Earth is to be seen neither as an ecosystem to be preserved unchanged, not as a quarry to be exploited for selfish and short-range economic reasons, but as a garden to be cultivated for development of its own potentialities...."

Environmental consequences do not stand alone. Each consequence is an holistic problem involving political, social, biological and physical elements. Concern with any one of these elements alone only creates more problems which lead to more problems which lead to more problems.

Socio-Economic Issues

The use of forests and associated vegetative communities for energy may become ecologically more acceptable than many other energy sources mainly because of the limited associated population problems. However, such use is fraught with many socio-economic consequences and constraints which deserve urgent attention and action if optimum results are to be obtained.

Emphasis and priorities may vary from country to country. Worldwide, people strive to maintain or improve their standard of living. However, some developing countries emphasize such concepts as life abundance for all, or self-reliance of people's participation as part of their strategy for development. These varying viewpoints on development goals put different shades of emphasis on socio-economic determinants of the use of any resource and could lead to differing paths of development even though the overall goal of any strategy adopted will still be geared towards human welfare and development.

Energy exploitation and utilization are issues of global concern, in spite of obvious differences among nations in terms of their varying socio-economic development. The use of forest resources for energy production will play a significant part in the alleviation of recent and current energy crises. A worldwide approach to planning and development of forest energy stocks will not only promote multinational cooperation but will also yield definite benefits, such as pointing the way for expansion of world trade, for transfer of technology and 'management skills, and for decreasing dependence on the use of fossil fuels.

Even though global approaches to the exploitation and utilization of forest energy resources are feasible, it is obvious that different areas of the world could develop particular and distinct, though possibly complementary, approaches which become necessary in view of the peculiarities of the socio-economic circumstances of each of these areas. Clearly, the approaches adopted by the world's developing and developed countries probably will be different, in degree if not in kind, because of the varying levels of their industrial needs and technological development. For example, approaches of the developed countries are determined to a considerable extent by the fact that the common source of energy is fossil fuels. The approaches of most developing countries, however, seem to be focusing on the important use of fuelwood for cooking and heating purposes.

There is a difference between the degree of socio-economic significance forest energy resources play in the developed and developing countries. In the former, energy from wood to sustain the existing level of economic development is unlikely in the immediate future and, at best, may be only a supplementary source of energy. Developed countries will continue to use wood for other purposes, but these uses probably will be small when compared with energy use. On the other hand, fuelwood remains the primary, if not the total, source of energy for cooking and heating in most developing countries; in some cases fuelwood constitutes more than 90 percent of the total energy needs. In general, changes affecting forest energy resources will probably have more far-reaching effects in the socio-economic milieu of developing countries than in that of the developed. The differences portrayed by developed and developing countries in terms of the relative importance of fuelwood are similar to those between urban and rural areas of many countries of the world. Fuelwood, for instance, is not as important in the energy requirements of people in the urban areas of developing countries as it is in those of rural inhabitants. Socio-economic consequences and constraints of the use of land and forests for energy are also less dramatic in the urban than rural areas.

Socio-economic circumstances of development in general, and that of the use of forest development for energy in particular, constantly are being affected by demographic changes in different parts of the world. As the population increases, pressure on land and other resources including forests increases. As a result, land and forests which were available for use at one time might become inadequate later simply because of rising population. The population in many developing countries has been increasing in recent decades out of proportion to other resources such as food and energy. Furthermore, the skills of the population have been upgraded through increasing educational input in the last few decades; this has resulted in increased income for workers who normally tend to give up using fuelwood for electricity or gas. There seems to be a strong correlation between income and upliftment status vis-a-vis the type of energy sources being utilized, although the conclusion seems irresistible.

Various technologies have been transferred consciously or inadvertently from the developed to developing countries, and the use of some of these have led to environmental damage. For example, power saws have become readily available property for the citizens of many countries. Mechanical equipment has conferred an unusual power advantage on the users, most of whom have used the power to humiliate the environment. In terms of the consumption of goods to which standards of living are equated, it often depends upon abundant supplies of energy.

Use of forest resources for energy has obvious advantages and disadvantages depending on how the socio-economic parameters of the use are handled. The advantages include a more or less permanent or dependable supply of energy based on the renewability of forest resources, an even spread of developmental activities through the afforestation of remote and/or economically or ecologically marginal lands, a generation of employment opportunities particularly in rural areas which are invariably closer to forest plantations, and so on. The disadvantages mainly are environmental or ecological. On balance, the world economy stands to gain significantly from the use of land and forests for energy.

Social Alternatives for Range Management

E. T. Bartlett, D. W. Ford, Gregory B. Greenwood & Jorge G. Medina T.

Department of Range Science, Colorado State University, Fort Collins, Colorado

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Rangeland Production and Human Population

Grazing lands, or more simply range, comprise a large portion of the earth's land area where climate, physiography and soils constrain vegetative development to herbaceous and shrubby types. The highest use of these lands for human welfare is often animal grazing for the production of products such as meat, fiber, milk and hides. Man and his animals have long been an integral part of ecosystems determining to a great degree the evolution of those ecosystems. Man's activities have been oriented toward the extraction of the harvestable portion of the ecosystem with little regard to long-term transformations of the ecosystems.

The situation might be summarized as one of man's actions transforming other components of the ecosystem, and those changes transforming man's behavior and activities—"Man's impact on man". Thus the problem is not new but has accompanied man throughout history. However, with greater demographic pressures from increasing human populations, the severity of the problem is greater, and consequently the effort to find solutions is intensified.

In the past several decades, the developing world has seen a great proliferation of projects and proposals that fall under the general heading of range and livestock development. These projects have attempted, directly or indirectly, to increase the welfare of mankind. They have not always resulted in success, and it is hypothesized that project failures have resulted from one or more components of the system. The purposes of this paper are: 1) to propose a framework which identifies components and actors of the general system, 2) to review activities that have been or might be used to benefit man, 3) to introduce several case examples which demonstrate how components and actors interact, and 4) to summarize concerns and recommendations for future actions.

Model of Range Use

The framework that facilitates the discussion of the system, the associated problems and solutions is a model of range use. A model can be defined as an abstraction of reality in which some phenomenon is to be highlighted. Clark and Cole (1975) identify four categories of models, two of which are symbolic and mental. Both are concerned with formal assertions made in logical terms; these assertions are in verbal terms in mental models and in mathematical terms in symbolic models. The model of range use is a mental model in which no mathematical relationships are given, although the mental assertions could be formed mathematically.

Structure

The model of range use includes the natural ecosystem, man and man's animals but is not limited to these components (Figure 1). Other components are included in the system such as society, political institutions, economic markets and so on. These components are at least equally as important as the first three and may be more important.

The primary actor in the system is the decision maker who plays the pivotal role in the model. It is he who must decide what actions will best satisfy his goals, and it is he who will reap the rewards or suffer the consequences of those actions. In the range situation, the decision maker is the pastoralist who interacts directly with the ecosystem. In most societies, the pastoralist appears to be the main decision maker. If the model was applied to a developed area such as the United States, the resource manager would need to be included as a decision maker and the interaction between the manager and pastoralist would need to be examined. The assumption making the pastoralist the major decision maker has an interesting implication in that the resource manager can only manage the resource through an intermediary—the pastoralist. Other disciplines would center the model on different parts—the economist on the market system, the anthropologist on society and its cultural system, the ecologist on the ecological interactions.

The model has been drawn such that similar components are located in the same general area. The upper components of the model are socioeconomic, and the lower are ecological; these interactions are specified and labeled with respect to the nature of the interactions. Thus, the

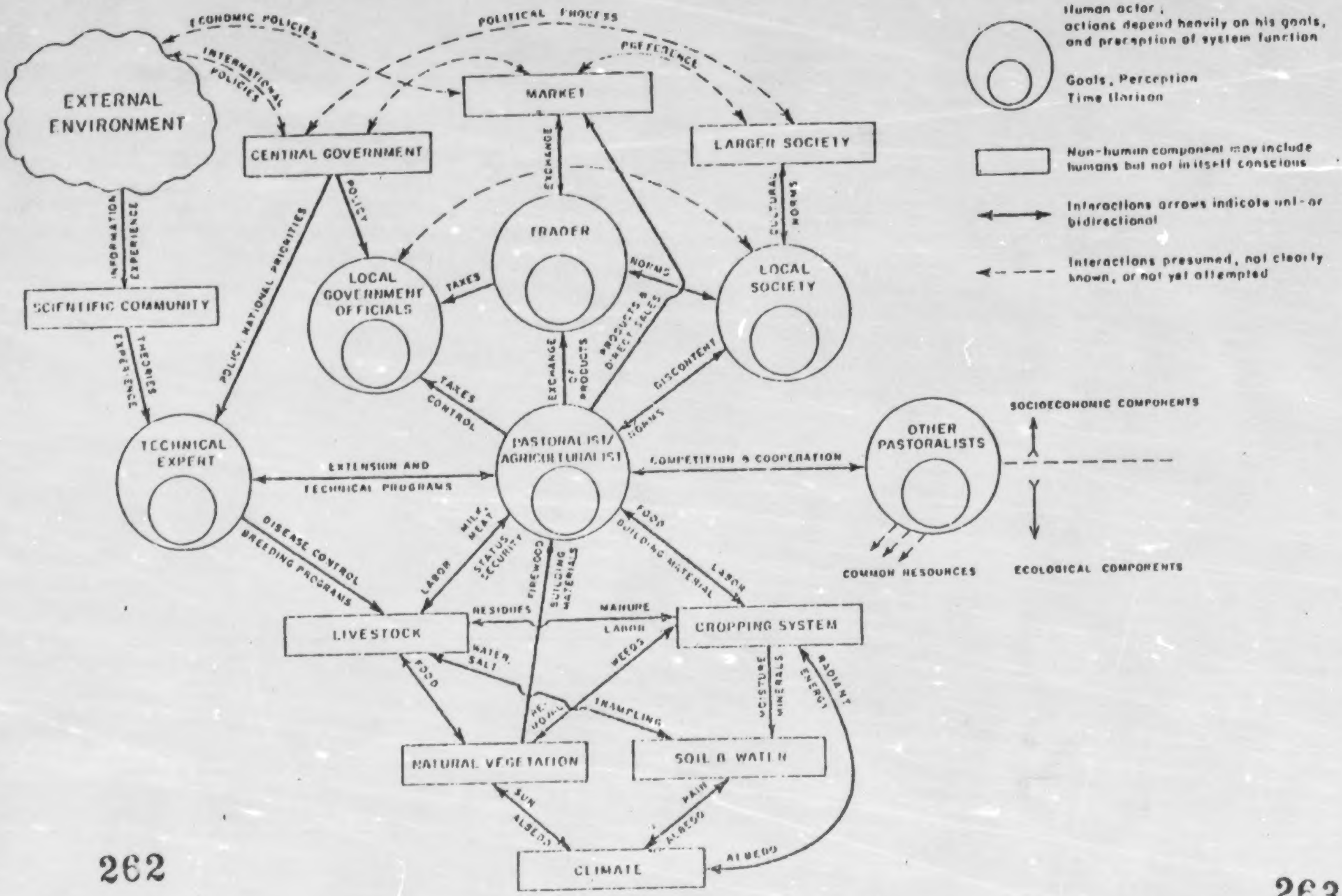
ECONOMIC POLICIES
POLITICAL PROCESS
INTERNATIONAL POLICIES
PREFERENCE
EXTERNAL ENVIRONMENT
MARKET
CENTRAL GOVERNMENT
LARGER SOCIETY
INFORMATION
EXPERIENCE
POLICY
EXCHANGE
CULTURAL
NORMS
POLICY, NATIONAL PRIORITIES
TRADER
SCIENTIFIC COMMUNITY
LOCAL GOVERNMENT OFFICIALS
TAXES
NORMS
LOCAL SOCIETY
PRODUCTS & DIRECT SALES
EXPERIENCE
THEORIES
EXCHANGE OF PRODUCTS
DISCONTENT
TAXES
CONTROL
NORMS
TECHNICAL EXPERT
PASTORALIST/ AGRICULTURALIST
OTHER PASTORALISTS
EXTENSION AND TECHNICAL PROGRAMS
COMPETITION & COOPERATION
DISEASE CONTROL
BREEDING PROGRAMS
MILK, MEAT
STATUS, SECURITY
LABOR
FIREWOOD
BUILDING MATERIALS
FOOD
BUILDING MATERIAL
LABOR
COMMON RESOURCES
LIVESTOCK
RESIDUES
MANURE
LABOR
CROPPING SYSTEM
WATER, SALT
WEEDS
FOOD
REMOVAL
TRAMPLING
MOISTURE
MINERALS
RADIANT ENERGY
NATURAL VEGETATION
SOIL & WATER
SUN
ALBEDO
RAIN
ALBEDO
ALBEDO
CLIMATE
Human actor, actions depend heavily on his goals, and perception of system function
Goals, Perception Time Horizon
Non-human component may include humans but not in itself conscious
Interactions arrows indicate uni- or bidirectional
Interactions presumed, not clearly known, or not yet attempted
SOCIOECONOMIC COMPONENTS
ECOLOGICAL COMPONENTS

Figure 1. The model of range use.

pastoralist-livestock interaction involves: 1) the livestock conferring dairy products, meat and social status on the pastoralist; and 2) the pastoralist who returns labor in the form of husbandry and protection. Similarly, the pastoralist both conforms to and, in a small way, alters the social norms of this community.

Interactions between components usually (and in the long run, almost always) result in the establishment of feedback loops. An initial change in one component reverberates through the system of interactions changing other components until the original componenet is itself changed. Certain interactions may involve direct and immediate feedback: the pastoralist and his livestock might be a good example. Other interactions lack direct feedback and may appear to be unidirectional; but in the long run, feedback does occur through an indirect route. A particularly interesting example is the climate-soil-vegetation interaction. Climate has long been known to be the major influence in soil development, but recently evidence indicates that regional denudation of the soil may intensify aridity (Hare 1977).

Feedback loops may be positive or negative, and because they are often only partially perceived, provide the mechanism for dysfunctions. A dysfunction is defined as an action that appears to cause the desired direct response on a component but through feedback results in the opposite response and failure.

In terms of structure, then, we have a model of a system involving both human actors and non-human components, linked by interactions. In the short run the interaction may appear to be uni- or bidirectional, but in the long run they always give rise to feedback mechanisms, involving variable time lags.

Function

Two characteristics broaden the utility of this model: its inclusive nature and its adaptability. The basic premise of the model is that interactions do exist. Exactly what those interactions are (their nature, direction, the lag times of the feedback loops they create, and the very bounds of the system itself) will depend on the particular environment to which the model is applied. In attempting to specify the interactions, the researcher can learn more about the system than he could in any other way.

System Dynamics

Once the structure of the system is specified, its temporal nature must be considered. Figure 1 might be considered as a cross-section of the system at a particular time. Through time, the feedback mechanisms can change the character of the components, e.g., the livestock population. the welfare of the pastoralist, the elaboration of social norms, etc. One would hope that over the long run these feedback mechanisms lead to some equilibrium, that is, that the system maintains its integrity (United Nations, 1977).

Equilibrium of a system does not always evolve. The system can also transform itself or be transformed by mechanisms only vaguely described such as politics, social change, or cultural change (Friedmann 1969). The overlay of the modern nation-state on the existing socioeconomic structure of pre-colonial Africa might be an example. In this case, a component that never existed within the system was added quickly, causing reverberations that continue today as central governments attempt to spread their control over vast hinterlands.

Component Operation and Perception

There are two major types of components in the model: the human and the non-human. In Figure 1, the non-human components are shown as boxes, and the human are identified by circles. It is assumed that the non-human components and their interactions are knowable and predictable in a comparative sense. For example, a great deal is known in range science involving the mutual effects of livestock, vegetation and soil. In fact, mathematical models have been constructed of temperate ecosystems. However, understanding of tropical ecology is far less developed (MAB, 1974); there is considerable uncertainty about the operation of the ecological components in the context of the developing world. It may be assumed that, through similar methodologies, the knowledge of these ecosystems is attainable.

More difficult to specify but perhaps of greater importance in the long-run operation of the model are the inner workings of the human components or actors. Behaviorists might argue that the actors act just as mechanistically or predictably as the non-human components. This assertion might be valid if there were time to run the experiments necessary to determine what the mechanisms are. However, the time is seldom available, and the actors' exact actions are unknown before they occur. Of course, one can speculate on the nature of the mechanisms that determine the actors' behavior.

A basic premise of economics is that people act to maximize utility. Exactly what utility means obviously differs between people and peoples. In maximizing utility each actor pursues goals. In terms of the model, goals might mean certain "quantities" attained in other system components within a given time period. Decisions are made, and actions are taken to reach established goals. This implies that all actors have some perception of system function, essentially their own model. This perception of the system provides the means to evaluate the proposed actions in terms of the desired goals. If the actors are frustrated in the pursuit of their goals, they perceive that they have a problem. It is important to note that such problems are the property of particular actors in the system, and not of the system itself. Thus, it might be expected that since all the actors in the system, including technical experts, may have different goals and different perceptions, there can be as many perceived problems as actors.

An illustration of different goals is provided by one important problem: desertification. In terms of the model, desertification has resulted from decisions by the pastoralist which weather conditions have led to a less productive system. An outsider's goal might be to manipulate whatever variables his knowledge indicates are pertinent to prevent a continued downward cycle. Depending on the degree of understanding of the system, action might be taken through the market, the government or some technical innovation.

A local government official might have a completely different goal and perception of the system evolution as he pursues his goal. His utility function might be described as maintenance of the existing political order through maximum tax revenues from production by the ecosystem. He may only dimly see how his tax policy affects the natural vegetation, but affect it he does, through the intermediary of the herder.

How does the pastoralist react to project personnel who talk about a deteriorating resource base, while the governor hounds him for taxes? He continues to maximize his utility according to his definition, and he affects the ecosystem in ways unforeseen and perhaps not all desired by other actors.

Several important observations evolve from this example. The particular perception of the system that each actor uses to evaluate the efficacy of his alternative actions has all the hazards that are encountered in building a model. He may encounter difficulty in specifying all the pertinent components of the system, as well as all their interactions. He must also attempt to predict what other actors will do, particularly difficult whenever he does not understand their perceptions of the system. His model may be very general in some areas, very specific in others. And, in the end, it may or may not serve the actor very well.

For example, good rainfall combined with technical innovations during the 1950's and 1960's allowed Sahelian pastoralists to greatly expand their herds, presumably increasing their welfare (Bernus 1975a). This expansion of livestock populations severely taxed the range's ability to support the herds and maintain itself at the same time. Thus, when the great drought of the early 1970's hit the region, the system virtually collapsed. It seems likely that both the range and the herds would have suffered much less in that drought if the herd expansion of the previous two decades had not occurred. Thus the pastoralists' attempt to maximize their welfare led paradoxically but inevitably to a general deterioration of their welfare.

It is difficult for technicians from developed countries to determine whether the pastoralist's perception of the system was deficient or if he had no alternative course of action. It might be argued that he did not account for the possibility of the drought, nor did he consider the results of all pastoralists acting exactly as he did. Another possibility is that he increased his herds during favorable periods essentially as stored wealth. The market and financial structures and, in fact, the culture itself may not provide a structure to store wealth. In addition, the pastoralist may have perceived that the method to best survive a drought would be to obtain as many animals as possible so that if a fixed percentage die, he still has more animals than if he had not increased his herds. (Glantz, 1976a, cited a Fulani herder: "I had 100 head of cattle and lost 50 in the drought. Next time I will have 200.") Thus he sees the inevitability of a drought but has no alternative. One of the current authors observed that many people in refugee camps in the Sahel did not seem to expect to be helped, although they did accept help when it was offered.

An important question to pose is how does the pastoralist react when he does not reach his goals—when, in fact, he may be getting worse off? Does he suppose that he was wrong in his perception or does he attribute the dysfunction to bad luck, fate, or the will of God? The same questions might be asked of the technical experts. The technical expert might recommend a better market system to remove animals from the range, increasing income to the pastoralist and providing greater tax revenues to the government. Yet the outcome is not clear—the pastoralist might react to higher prices by selling fewer cattle for the same amount of money since his utility function is maximized by cattle, not money (Khalifa and Simpson, cited by Glantz, 1977). Does the expert suppose that he perceived the problem incorrectly or does he perceive that the other actors had misperceptions?

A corollary to the perception that each actor uses to evaluate his effectiveness is that each actor's goals may eventually be shown to be internally inconsistent. Thus, the pastoralist whose set of goals may include having many head of cattle, lots of green grass, and no government officials may find that by pursuing one goal (more cattle) he may not only frustrate other goals (reducing forage) but may also bring about frustration of all his goals. His cattle die from starvation, and there is an influx of officials to determine what is happening and why.

Depending on uncertain knowledge of the ecosystem and the actor's goals, it might be possible to determine the relative imcompatibilities within a goal set. Yet ascertaining the optimum level of goal satisfaction both within one actor's goal set and between goal sets of all actors depends on actors realizing that they are constrained, i.e., that a gain on one front requires a loss on another. It seems quite likely that these tradeoffs can almost never be determined beforehand, even by the actors themselves, but must be played out to be realized (Lindblom 1959). However, these conflicting goals must be identified and included in a model of range use if any progress is to be made.

The Role of the Technical Expert

How does the technical expert become involved in this system? Usually he becomes involved at the behest of a government. The government has a problem; it may be one of insufficient production, of desertification, or of difficulty in making itself felt throughout the territory. For the sake of discussion let us choose desertification as the problem to be addressed here. The problem of desertification has received much attention recently and, in fact, has been mentioned previously in this paper. Examples in the sections that follow will not be confined to this problem; however, it serves here to delineate the role of the technical expert. While an expert from a developed country may feel that desertification is the "real" problem, it is crucial to understand that his perception is but one of the many interacting perceptions of the direct resource use (Glantz and Katz 1977). The model which includes the expert as one of the many actors suggests several ways in which the problem can be solved.

Knowledge

Any expert's goal must be operationally defined. It must specify a system state that is measurable and ecologically feasible and which indicates that the problem is being resolved. This means that there must be a fairly complete understanding of the ecosystem and what it could be expected to produce.

It would be helpful to understand the goals, perceptions and problems of all actors so as to better anticipate their reactions to interventions. For the pastoralist such research might cover such topics as: 1) his self-perception as herder/farmer, 2) the functions that livestock and crops serve, 3) the relative importance of social structures, and 4) his likelihood of reacting to market incentives. For a government official, interest might be centered on: 1) his sense of service, 2) his identification with the present regime, and 3) his self-perception (functionary vs. change agent). Given such understanding it might be possible to determine certain points of potential conflict where some goals of different actors, again the experts included, are incompatible.

If the above tasks were accomplished, the model would be fairly well-developed. Such research, though, cannot be considered in a vacuum. To illustrate, local government officials often state that enough reserach has been done and that what is needed is action. The model explains their behavior as follows. They perceive a problem, largely one of acting like an effective government and not a university. They feel compelled to do something for their nation. Their goal is to act—to use their power. What their acts are designed to accomplish may not be clear to other actors. It is very possible that what they would do is not ecologically sound and may in fact exacerbate desertification and the pastoralist's problem of maximizing his welfare; it may even be politically counterproductive. Yet their problem is a very real one; their desires are very commendable.

Communication between actors is necessary to define the problem and to select possible solutions. One action that could conceivably contribute to the solution of several problems is that of involving the local population in the ecological research in order to obtain a better understanding of the system (MAB, 1974; United Nations, 1977).

Interventions

Assuming that the model could be specified, the impact of different interventions on the system could be evaluated. It could be determined whether a technical innovation such as a new pricing system or new legislation would move toward or away from the operationally defined goal. In a way this implies a behavioristic approach toward other actors; parameters are changed and the actors react differently yet consistently in light of their own utility functions. Such an approach might lead to several actors agreeing on a particular intervention but for different, and possibly fundamentally different, reasons. Many of the projects to date have been of this type and their results have seldom been good, usually because of dysfunctions arising from a lack of understanding of other actors' modes of operation. At least in range management one wonders if any technical solutions exist that further everyone's goals while requiring that none of them be changed.

Through understanding of the system it may be found that no interventions of this manipulative type would move toward the desired system state. That is, the desired state cannot be attained except by altering in some way the perceptions and goals of the other actors. Action might be taken to coopt other actors, or actions could be initiated that change the institutional system or culture of the actors.

Educational programs may have the greatest chance of long-term success. Such programs involve developing interpersonal skills, and promoting an understanding of other actors' perceptions. They may even use technical innovations that are in the short run inimical to the goal, but that create trust and cooperation which may be more important in the long run (Arensberg and Niehoff 1964).

Summary

Most decision makers or technical experts can recall projects of the various types discussed above. The purpose of this section is to stress that all of these projects are related; they all seek to solve problems perceived by the project formulators. The success or failure of such projects can be explained by the accuracy of the formulators' understanding of the ecosystem and of the other actors and their goals. Projects and proposals fall into four basic categories:

1. Information gathering.

2. Behaviorist innovations, usually technical, which change some of the parameters of the system, but not the actors' perceptions.

3. Educational programs, which seek to alter the perception or goals of acto alter the perception or goals of actors.

4. Institution building, which seeks to transform the system.

Solutions that are currently being attempted and solutions that are available but little used are discussed in following sections. These alternatives will be discussed with respect to the above classifications and the context of the model of range use.

Range Problems and Solutions

Problems encountered on rangelands in developing regions of the world can take on many forms and are often quite difficult to identify. Practical solutions to these problems may be even more complex. Comprehension of and the solutions to range problems begin with a detailed evaluation of the system involved. The inde 1) should be considered both individually and as parts of the whole so that the consequences of any future actions might be traced. Thus, the transformation of the range into a productive unit for the benefit of man involves the identification of the most critical variables constraining the productivity and an understanding of the functioning of the entire system.

The present molding and deterioration of rangelands can be attributed to some combination of: 1) the pastoralist's management and exploitation practices and 2) the limiting factors and natural fluctuations of the physical and biological environment. In arid areas the only environmental change due to natural causes has been due to periodic droughts with the resultant short-term effects (Warren and Maizels 1976). However, those processes of change induced by man and his available technology tend to persist for much longer periods of time.

Even though range problems can adopt a multiplicity of forms, the main indicator of range degradation is the sustained decline in yield of both vegetation and livestock. The net impact of overgrazing is low production per animal and per hectare, a symptom of suboptimal utilization of forage and low rangeland productivity (Mott 1960). A procedure for evaluating desertification and the actual state of pastoral areas has been proposed by Warren and Maizels (1976). Their synthetic approach includes the following steps:

1. Selection of homogeneous land units.

2. Selection of key ecological factors.

3. Assessment of the condition and trend of key factors.

4. Identification of threshold and critical conditions to identify ecological constraints.

5. Development of an integrated scale of degradation on a land unit basis.

6. Determination of constraints amenable to treatment.

7. Recommendation of a management strategy for maximum long-term production to halt deterioration and restore stability.

This methodology only focuses on the natural resource component and does not account for human influences. It provides a guide to evaluate the vegetation-soil-animal subsystem of the range as though it were independent of or isolated from man. The solutions provided by this methodology are dependent on information gathered from the production-related sybsystem; however, different answers are obtained from the point of view of anthropic optimization (Riveros and Gasto 1978). In order to overcome this problem, Nava et al. (1979) conceptualized the ecosystem as the unity of man and nature; its state at any given point in time and space is bound to an interrelated set of social, economic, physical and ecological variables. In this form, any methodology for studying and evaluating the range resources to generate management alternatives of social interest must include biogeostructure, sociostructure, technostructure, and internal and incident systems. These components correspond to the natural resource, human organization, infrastructure (material, economic and technical), surrounding environment, and exogeneous variables, respectively.

The development of an approach to study such components was undertaken by Maynez and others (1975). Their methodology considers the ecosystem as a patient whose state may be normal or abnormal depending on whether or not the functioning characteristics correspond to a given level of man-channeled productivity. It consists of five successive and coordinated steps: clinic examination, diagnosis, treatment, strategy, and verification. The approach is based on two assumptions: 1) the existence of an optimum state which may be defined by anthropic criteria, and 2) the feasibility for directing the process of change of the whole ecosystem towards this optimum state. The range resources constitute only one component interacting with several elements of a diversified nature, of which the most important are man and his socioeconomic structure (Riveros et al. 1979a).

Once the range components have been identified and analyzed, the next consideration is the definition of transformation alternatives or management activities aimed at the optimum utilization and productivity of the range for the benefit of man.

Alternative Solutions

In seeking solutions to the development of pastoral areas one must be concerned with specific objectives of the planned change. Development can be seen in terms of: 1) the aims, and 2) the means employed. In the first case, the development process is viewed as a dynamic end-state having as its fundamental goal the achievement of better styles of life. In other words, it provides a whole set of opportunities for the fulfillment of the physical, mental, social and economic development of the human personality (Streeten 1977; Goulet 1977; McGranahan 1972; Lenero and Trueba 1972). In the second case, development concerns specific ways in which the overall purpose of the project will be accomplished. This involves material needs, capital, persons or organizations, services, and actions oriented to give specific solutions to particular problems (Armijo et al. 1976; Seers 1977).

Consideration of short-term vs. long-term solutions must be taken into account. Heavy grazing could result in higher monetary returns per hectare in the short run than could strategies involving medium and light grazing. However, in the long run such solutions often result in wide fluctuations and a sustained decline in return. Therefore, short-run solutions can result in long-term system instability. This is a matter of choosing present vs. future use of the resources.

In this context the recognition of a need by the people, who are both the subject and object of development, has an extremely high priority in the adoption of technology. The behavior of the pastoralist as imposed by the widely fluctuating environmental conditions is highly indicative of the reluctance of the people to accept the introduction of new technologies. Thus for a degraded range, general destocking and developments such as fencing and watering points could be helpful in reversing the negative trend of the range. However, the local population might be against risky investments; they may be more willing to accept management alternatives which would be less capital intensive even though they may take longer to be beneficial.

For the pastoralist solutions to range problems would appear to fit into the framework presented in Figure 2. Complex interactions between physical, ecological, social and economic factors constrain and limit the applicability of any given technological strategy (Nava et al. 1979). Alternatives selected from possible range improvement and management techniques need to meet the particular physical requirements of the area. Appropriate questions are: what will be the long- and short-term ecological consequences, what kinds of treatment are more appropriate for the flood plains vs. the sandy hills or slopes, what species are more adapted for reseeding in the area, what grazing system and what kind of animals are best suited for proper forage utilization in terms of intensity, frequency, season and distribution of the grazing.

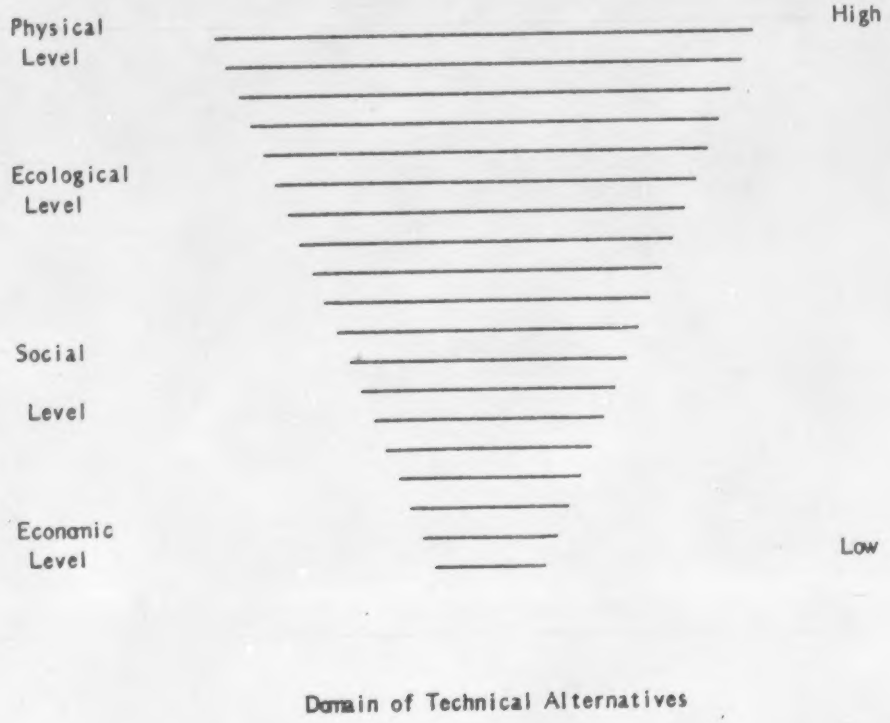

Figure 2. Levels for decision-making in natural resources problems (Nava et al, 1979).

Solutions must also fit into the social structure and cultural context of the region. It is necessary to properly evaluate whether an alternative solution addresses the needs, perceived problems and goals of people. For example, the implementation of watering points may make it possible to run additional cattle on the range, but this may not be what local people need. There may be alternative solutions that more genuinely reflect the people's perceptions of the problem. Approaches should encourage participation in the proposed project, and strategies that can be successfully used for organizing the people identified.

Finally, before implementing any project an economic and financial analysis is needed to estimate its profitability and incentives. Funding for production and maintenance must be available, and the local labor force must be sufficient to handle the required work. Also, if a part of the project requires specific training of unskilled labor, provisions have to be made to implement such training.

From the above considerations it is fairly obvious than not all proposed solutions will meet the preceding criteria. Nevertheless some sort of action must be taken. In practice the eradication of all felt problems at any given time is almost impossible because it implies the utilization of resources that are not always available. For this reason a given development policy must allow for a prioritization of problems and goals. If the questions of who and how to establish priorities are answered, the management activities can be implemented so that in a sequential form they will tend to reduce problems witnout creating additional conflicts (Jameson and Medina 1978).

Direction of Solutions

The technological progress achieved in recent decades has been a direct result of the enormous contribution of science for extending our domain of the world. However, this progress is not automatically converted into development. Cultural diversity, social and economic heterogeneity, and ethnic variations produce a heavy load of ethical and moral values from which development projects cannot be disassociated. For instance, the conception of man as master of nature has influenced western modern science and technology changing man's attitudes from reverence to the exploitation and utilization of nature for human goals (White 1967; Richter 1972). Man has been compelled to intensively transform his surrounding environment in order to meet his increasing food demands and/or his needs for open space recreation. Rangelands have not escaped from this trend; at the present time, they constitute one of the more extensively used resources in arid and semi-arid regions of the world.

Two types of solutions to range management problems are commonly used: 1) the molding of social-economic structure of a region to a particular technology, and 2) the adaptation of a technique to a region. This is viewed as the difference between "soft" and "hard" technology. The first type emphasizes the use of improved operations, procedures, and management methods, whereas the latter involves new equipment or new or improved material infrastructures. As the model of range use suggests, the problem of improving a rural community cannot be reduced to a simplistic view. However, to facilitate the analysis of proposals and projects for solving range problems, technologies have been grouped into four basic categories: Information gathering, behaviorist innovations, education and institutional change.

Information Gathering

In the identification, design and implementation of a project, the process of information gathering and analysis helps the project manager to make better decisions in terms of (Morse et al. 1976):

1. Collecting data which allows for the selection of the most promising project,

2. Collecting data which will allow for the specification of project parameters, and

3. Collecting data to be used in monitoring project activities, evaluating project success, and analytically diagnosing the strengths and limitations of the project.

The information collected may be used directly or may provide a data base for use with other techniques. Table 1 presents some data requirements for range development projects. This information is used to determine whether a proposed technology can be tailored to the local environment. If this is feasible, the information serves in the specification of existing production and socio-cultural patterns, and in the determination of changes which must take place if the alternative technology is to benefit project participants (Morse et al. 1976).

Behaviorist Innovations

Behaviorist innovations are used whenever the manager decides that changes are necessary in order to alter the way an operation is run. These solutions carry the basic assumption that the problem itself can be isolated and that some existing techniques can be selected so as to solve that problem without creating any others. If proper range use is not adhered to or if the land is pushed beyond its normal carrying capacity, it is often necessary to utilize behaviorist techniques to reverse undesirable range trends. In these cases an approach involving a natural recovery of the range is thought to be economically prohibitive. It follows that range improvements involve the application of special treatments and strategies, i.e., the building of certain water developments or fencing facilities, which allow for or facilitate increased use of the range (Vallentine 1971). Techniques can be divided into two categories: 1) those having short-term effects, and 2) those having long-term effects. In the first case, the vegetation is manipulated through pyric, mechanical, manual, chemical, or biological treatments as well as reseeding and fertilization practices, contour furrowing, water harvesting and other special treatments to improve the infiltration of water in situ or reduce soil erosion (Heady 1975; Stoddart et al. 1975). Animals can be managed by controlling their number, kind, and distribution on the range by fencing, water development, salting, herding, construction of livestock trails, corrals and roads, and by the development of special-purpose pastures.

The main objective of range management is to increase the productivity and stability of rangelands. However, the rate of the change will be determined by factors such as the particular kind of range ecosystem and its degree of depletion, the climatic conditions or fluctuations, the plan of improvement, and the overall management efficiency of the project.

Education

This category of projects includes formal and informal educational programs which seek to support the development of a self-reliant process among pastoralists. The educational perspective would allow people to perceive their problems more clearly, to define and examine them, and to decide on specific solutions (Lassen 1979). Such education attempts to provide people with the appropriate information needed to make decisions. Agricultural extension represents one of the most widely used approaches oriented towards this task. On the other hand, the "consciousness-raising" approach of Freire (1970; 1974) is representative of the conflict methodologies; it emphasizes the process of building up the self-dignity and decision-making capacities of the oppressed rural poor in the less developed countries. That is, rather than accepting the existing practices or authority, people are encouraged to perceive themselves as active, creative subjects capable of examining critically, interacting with, and transforming their natural-social complex.

Table 1. Information requirements to support rural development projects (Adapted from Morse et al, 1976).

Phase	System	Data Category	Data Needed	Data To Be Used To:
Identification	Production-related		Production Environment	Determine potential of pastoral environment
			Production Techniques	Determine most efficient local technologies now being used which will affect speed and magnitude of new change to be introduced
			Possible Technologies Applicable to the area	Determine how long it might take to develop improved technological package
	Social/Cultural Related	Goals	Size, dispersement of target population	Determine size of overall program the magnitude of
			Obvious bottlenecks and constraints	Determine major obstacles to be overcome
Design	Production-related (within area)	Technology for herders	Existing production pattern	Determine degree of change for new technology
			Past livestock history	Determine appropriateness of alternative technology
			Soil/weather/blight/drought/special condition	Determine special constraints to alternative technology
			Livestock calendar	Determine time constraints on new endeavors
			Availability of adaptative research institutions	Determine mechanisms for tailoring technology to local conditions
			Alternative technology used by large herders	Determine if other technology could be adapted for use by small herders
		Transferring knowledge to herders	Spread pattern of new technology	Determine the rapidity of existing extension and knowledge transfer channels
			Impact of existing extensionists	Determine the existing extension and knowledge transfer channels
			Willingness to try new production methods	Determine degree of extension services required for new technology
		Services available to small herders	Landholding, tenancy, improvement recapture, rent or purchase arrangements	Determine the obstacles to production change resulting from landholdings and usage patterns
			Variance in landholding, land used	Determine the relative wealth dispersion in the area
			Land used in relation to land held or available	Determine the potential for expansion of land under utilization
			Labor use calendar	Determine labor constraints to new technology
			Labor requirements by skill level	Determine alternative labor sources
			Livestock supplies used, their availability & price	Determine the requirements for the project to provide supplies

Table 1. (continued)

Phase	System	Data Category	Data Needed	Data To Be Used To:
		Credit for small herders	Cash/credit availability by source for innovation	Determine if credit will be a necessary part of project design
			Credit use by supplier	Determine if local mechanisms could be used to supply institutional credit
			Credit rates, by source	Determine the constraints to new technology from interest payments
			Credit repayment history, by source	Determine how institutional credit, if needed, can be distributed and recovered
		Marketing Production	Percent of present output sold for cash, by animal type	Determine present involvement in cash market (may affect subsistence and risk)
			Marketing networks; local, regional, national prices	Determine whether project must assist in the marketing of new output
		Profitability and Risk	Relative prices of inputs and outputs	Determine profit margin of present technology
			Cash requirements of present production techniques	Determine the return to cash from present technology
			Cash requirement of alternative production tech.	Determine risk on upfront cash, return to cash from alternative technology
			Surplus above subsistence	Determine level of disaster if new technology fails
			Local assistance in instances of failures	Determine if mutual assistance mechanisms help take some risk out of innovation
	Production/related (outside area)		Alternative technologies developed elsewhere, other development projects which might fit the local production environment	Determine largest possible set of options for technological innovations which might be applicable to the project area
	Social/Cultural-Related	Local leadership pattern	Influence pattern of local leaders over change	Determine who must be convinced of the need to innovate
			Small-group leaders	Determine who should be selected for more extensive demonstrations
			Extent of leadership influence	Determine whether local leadership can resolve disputes, enforce contracts, etc.
			Leadership cohesion with the target population	Determine whether existing local leadership can be expected to support income benefits for the target group
		Local Organization	Herders' associations or other functional organizations	Determine whether existing organizations could be used as development intermediaries

Table 1. (continued)

Phase	System	Data Category	Data Needed	Data To Be Used To:
			Other traditional or community organizations or groups	Determine if these organizations could be transformed to complement the project
			Past history of cooperation in the locale	Determine if there are unresolvable problems or potential for positive local or district associations
			Social cohesion in production and exchange of goods	Determine if the society can accept mutual responsibilities & obligations
		Local Social/ cultural system	Constraints to personal accumulation of wealth	Determine adequacy of income in the incentive system
			Constraints to community endeavors	Determine division of public and private development efforts
			Constraints to cooperate with others in the target population	Determine homogeneity of target population
			Perceptions of outsiders, own population, gov't., etc.	Determine who should be the entering wedge for the project
		Local Political System	Basis of local gov't., power and responsibility	Determine the likely commitment of governing body to the target group
Implementation			Ability of local gov't. to draw upon outside support	Determine the role gov't. should/can play in project
			Monitoring System	Determine if project is operating efficiently within established guidelines
			Evaluation System	Determine results of project, total effects of project and identify and diagnose problems
			Analysis, Feedback and Revision System	Provide a quantitative and qualitative analysis of the results and the reasons for the results

The educational strategy should include some ways of increasing the participation of a project's beneficiaries. Possible participation opportunities for local people are (Lassen 1979):

1. Participation in the decision-making phase of a project,

2. Participation in the implementation of a project,

3. Participation in the evaluation of the performance of project administrators, and

4. Participation in control of how a project is directed in the long run.

From another perspective the formal university training of the project manager, technical expert, or change agent can provide him with a highly sophisticated ability to identify technical problems that local people may not identify or perceive as threatening to their survival. For this reason, local people will react skeptically to most technological innovations unless their perception of the problem is altered. Most cross-cultural projects are characterized by marked differences between local people and technical experts in the perceptions and prioritization of problems. Therefore, the training of change agents ". . .must be based on a knowledge both of scientific research and of field knowledge and problems of active pastoralists. . ." (Warren and Maizels 1976).

Institutional Change

This category calls for varying degrees of reorganization and transformation of existing organizational structures in order to shape sustained group action within and among rural communities. Grazing systems fall here, as well as pastoralist cooperatives, human development programs, insurance plans, land ownership patterns, project management committees, agricultural research and extension, and government rural development agency coordination. Often the implementation of a needed solution to a range use problem does not result in the expected benefits unless a concurrent change is instituted inside or outside the pastoralist community. A particular grazing plan, for example, may be necessary to implement certain range improvement procedures; yet, legal land tenure aspects could prevent proper management. This is the case of the common rangeland used by many rural societies in developing countries. Here, the rangeland is owned by the community and any member has the right to use it without a special provision or commitment for its further development or improvement. In addition, only a few members of the community own most of the livestock. Therefore, these few benefit at the expense of the rest of the community (Guzman et al. 1978; Fernandez 1975). Such situations call for changes in the traditional utilization of common rangeland for successful project implementation and for increased distribution of benefits.

Summary

The cumulative experiences in range development projects for agro-pastoral societies in the less developed nations of the world make manifest the need for fresher approaches for the fulfillment of the fundamental goal of improving people's condition. A particular project may be oriented in four different directions: information gathering, behaviorist innovations, education and institutional changes, which individually and as a whole affect all the components of the model of range use. This provides a basic framework for the evaluation of specific actions within each category of project proposals, past, ongoing or future, and their impact on the range productivity, herder's welfare and social status, and the perception of the change agent.

Case Examples

Three case examples of rangeland use are presented and represent situations where rangelands have been degraded in different areas of the world. The first example is the Sahelian region of Africa with particular emphasis on Chad. The second is the Chihuahuan Desert region in Mexico, and the third is the Navajo Reservation in Southwestern United States.

The purpose of the case examples is to demonstrate how components and actors of the range use model interact, and to discuss specific range development projects. For each case example a description of the ecological and social systems is presented, followed by a history of interventions in each area. The values and perceptions of the pastoralists are emphasized and related to current projects.

The Sahel

Description of Milieu

Abiotic

The Sahel is the part of Africa stretching east to west across the continent just south of the Sahara Desert. The region's name is derived from the Arabic word for edge; thus, edge of the desert. It has a generally dry climate, with precipitation increasing from 100 mm in the north to 500-600 mm in the south (Bernus 1975a). North of the 100 mm isohyte lies the desert with its permanent aridity. Toward the south the Sahel grades into the savanna, the Sudan.

The rainfall in the Sahel comes with the high sun between June and September. The Sahel receives virtually all of the annual rainfall during this four-month period. Weather records also show a very high degree of variability in precipitation, both spatially within a season and temporally between seasons. Following the summer rainy season, cool dry air blows out of the desert and dominates the weather for the next four months. In March as the sun moves north, the cool wind stops and the region begins to heat up, reaching highs of 45° to 47°C in April and May before north-moving clouds reduce the insolation prior to the advent of the rains.

Several plateaus occur in the Sahel and have furnished sediments in the basins laid down by rivers of the region, notably in the Lake Chad Basin and the basin of the Bend of the Niger. Lakes of continental scale occupied the basins in the Quaternary Period; Lake Chad is a remnant of such a lake. Drought periods during the Pleistocene Epoch allowed for the reworking of the fluvial sediments and the creation of ergs, sand seas, that remain today, often stabilized by grass and trees (INTSH 1972). The soils of the Sahel follow the general climatic regime as modified by the local topography, leading to heavy lacustrine clays, the sandy soils of the ergs and river valleys grading up to the southern laterized sands and gravel of the plateaus. Some areas, particularly the higher parts of the plateaus, show very little soil development (INTSH 1972).

Biotic

The wildlife and vegetation of the Sahel display behavior adapted to the long dry period. The herbaceous plants have dormant stages, and most of the trees have deciduous leaves and long tap roots as well as broad surface root systems.

The northern Sahel has an herbaceous steppe, often formed on the fluvial or aeolian sands. Wadis (beds of intermittent rivers) often interrupt the steppe. The wadis carry water only during the short rainy season, while the steppes are generally dry with the water table usually 50 m below the surface. As such, herders use these steppes only during the wet season. The steppes form the northernmost point of the transhumant circuit.

The plant community of the southern Sahel is floristically different but also serves as wet season pasture. Trees and shrubs become more important toward the south, but the availability of livestock water still limits the grazing season.

The southern Sahel also has numerous clay lowlands and floodplains which are often inundated during the rainy season and avoided by herders. As the water recedes from the lowlands, herders move their cattle onto these pastures during the dry season. Tall growing perennials cover these pastures. Herders often burn off the wet season growth to trigger new green growth during the dry season. As the dry season progresses and the herbaceous forage is consumed, trees and shrubs become more important forage sources.

Economic

The vast majority of Sahelian Africans are employed in traditional occupations. These occupations include farming of millet, sorghum and beans, herding of cattle, sheep, goats and camels as well as traditional urban occupations such as traders, Koranic teachers and blacksmiths. Development in its various forms has created new job categories such as school teachers, administrators, nurses and mechanics for bicycles, kerosene lamps and radios.

Traditionally, the distinction between farmers and herders has not always been clear. Certainly some are strictly farmers or herders; yet it is quite common to find farmers that own cattle or sheep and herders that plant and harvest millet. Thus, each group divides their labor in various proportions between farming and herding. Others have only recently begun to experiment with the opposite technology. Herding or at least owning cattle is a relatively recent innovation in southern Chad, just as millet cultivation is for some groups in the north.

It is important to realize that both traditional transhumant (transhumance is a system of seasonal herd migration following a well-defined route reflecting seasonal aridity vs. nomadism which reflects erratic search for pasture and occurs under a desert regime) livestock raising and traditional shifting agriculture were relatively well adapted systems of resource use (Bernus 1975a; Johnson 1975). It is not at all surprising to find an intergradation of farming and herding since southern Sahel presents opportunities for both activities. Horowitz (1972) explained the segregation of the two activities on the basis of social mores, not ecology.

Though rural Africans, particularly pastoralists, are essentially traditional, they are open to innovations that correspond with their value systems.

> I know of no group, not even those very isolated, who do not have some notion of improvement, of modernization, if only the wish to be less the victim of inequality in the face of sickness and death (Tubiana 1975).

In the realm of livestock,

> where some development was clearly and immediately "beneficial", such as water development, then it was accepted without hesitation, but where it was not obviously beneficial then some form of demonstration was necessary. The secret of success in such cases was to make the demonstration in a context as familiar as possible to the pastoralist, otherwise it would be thought of as another "government scheme", born of incomprehensible technology and endless funds (Baker, R. 1975).

Many articles of African resource use give the impression that land use was traditionally chaotic and unorganized. Yet, the current state of land use control may not reflect African traditions. There are several examples of traditional land use controls, particularly where there was a fairly homogeneous population and a clear power structure. Gallais (1975) describes the types of pastures recognized by the Fulani in the Niger Delta in Mali and their pastoral code (dina) which restricted access to dry season pasture. Paul Baker (1975) and Bernus (1975a) both discuss the rising tensions between pastoral groups as a result of the breakdown of traditional regional hegemony.

Another mistaken impression of African livestock production is that of a poorly developed marketing system. In fact, the movement of cattle for sale can often cover hundreds of kilometers and involve a fairly elaborate system of intermediaries, buyers and drivers all commissioned by one cattle merchant. The major movement is from north to south toward the more populous and red meat deficient zones of the humid savanna and forest with lateral movements toward centers of population, particularly Nigeria. Considerable profits accrue to the cattle merchants because of the regional price differential. The price for cattle in Maiduguri, Nigeria (300 km from Chad) is three to five times higher than in Chad.

Social

Most Sahelian societies are deeply influenced by Islam. While the effects of Islam are manifold, certain practices such as the pilgrimage to Mecca (haj), the fast month of Ramadan and the two major feast days have strong economic overtones. For example, the price of sheep can triple in the weeks preceding id al adha, a feast day that requires the sacrifice of a sheep. Also a certain fatalism can be attributed to the influence of Islam. Disasters are often explained away as mugaddar, Arabic for fated.

The societies are not always homogeneous; minorities exist in many areas. Haddads in Chad and Bororos throughout the Sahel are good examples. Haddads whose name derives from the Arabic word for iron were originally blacksmiths, but now do a wide variety of jobs. They are often excellent farmers of millet and gardeners in the wadi gardens, but are generally viewed as social inferiors by their neighbors.

Bororos are racially related to the Fulani, but have resisted the urbanizing influence of Islam. (Fulani is the Arabic name for these people, also called Peulh, Fulata and Mbororo—they have traditionally been regarded as foreigners.) They herd livestock in the bush. They are strikingly different from the surrounding peoples, and are viewed as bizarre, occasionally dangerous, but useful for some household tasks (pounding of millet to flour) and for raising cattle.

Cultural shatter zones exist throughout the Sahel, i.e., areas that, while generally Moslem, are inhabited by many different groups. For example, within the sousprefecture of Massakory, east of Lake Chad, eight different groups live and speak four different languages although one, Arabic, is generally understood. Such intermingling reflects a turbulent past, with different groups vying for power throughout history. Such a heterogeneous area will present problems and opportunities very different from those of a homogeneous zone (Gallais 1975).

Interventions in the Sahel

In reviewing the history of intervention in the Sahel, it is helpful to remember that interventions in Africa have a long and checkered history. In particular, the effect of domination and colonization by the European powers, superseded by the independent governments, must not be overlooked.

Administration

There is evidence in some areas that effective land use control existed prior to colonization but was destroyed by colonization.

> Historically, it is hardly possible to avoid the question of the consequences of administrative action in the colonial period, oriented toward the establishment of political domination based on force and when necessary on the physical liquidation of opponents (Monad 1975).

Political actions aimed at reducing local power also reduced or destroyed the land use controls exercised as part of the tribal power: an excellent example of a dysfunction arising from an attempt to transform the system.

Ranching

One of the earliest developments in the realm of livestock and range resource use was the establishment of ranches in the Sahel. In Chad, these ranches were run by private companies and were models of rational range use, complete with fences and deep water wells. Neither of the ranches in Chad are presently operating. The most common reasons for their failure are isolation and marketing difficulties. In any event, the ranches did not parallel the means of production used by local pastoral peoples and surely could not have been expanded to cover large areas of the Sahel without causing serious problems for other resource users. Ranches are examples of extractive technical colonial enterprises that use local natural resources but only involve local people as salaried workers. In terms of the model, the ranches were new institutions that competed with local pastoralists for range resources.

Water and Veterinary Services

The interventions that directly touched most of the livestock owners in the Sahel are the establishment of: 1) a veterinary system, and 2) a network of water developments. Both are behaviorist interventions that sought to and did change parameters of the system. Both provide examples of interventions that led to great ecological disturbance even though most agreed that they were "good".

In essence both interventions removed two major limiting factors on livestock population. The vaccination allowed for a more rapid increase in livestock population, while the establishment of water wells changed the usual migration routes converting previous dry season pasture to year-round pasture and concentrating the increasing livestock populations around wells.

It is interesting to speculate on the perceptions of the pastoralist. Herders to this day still maintain that what they need most are more wells, probably because water is not developed in unexploited areas. Digging wells and watering stock are very difficult tasks, and any technological improvement is welcome (Bernus 1975a). Yet, herders are aware of the effects wells have, the tradeoffs that are to be made between their labor and the condition of the range. At least one survey in Niger in 1972 showed that the pastoralist preferred cement wells to mechanical pumping stations because open wells were easier to use and open wells reduce the threat of overstocking, possibly because fewer cattle can be watered by hand than by pump (Monad 1975).

What the project formulators foresaw is less clear. Certainly they must have understood that they were removing two major factors limiting the expansion of livestock in the Sahel. One wonders if they went so far as to ponder the nature of the new limiting factor or to imagine that increased herd size automatically meant greater offtake in the market sense. The goals of the formulators had nothing to do with perception of ecological limiting factors, but were political. Most of the vaccination programs and water development programs were financed by colonial governments and foreign aid organizations. These projects were relatively easy to implement, had results measurable within a politically expedient time frame, and demonstrated good will, both on the part of the foreign governments and developing nations' governments.

The effects of these two interventions, compounded by the natural increase in the herder population, have been documented elsewhere (Glantz 1976b; Bernus 1975a), but they resulted in rapid growth of livestock populations during the relatively wet years of the 50's and 60's. This growth was followed by decimation of the herds during the early 70's when a 50 to 100 year drought drastically reduced forage levels. Forage became the new limiting factor and equilibrium was re-established, but at a much lower livestock population.

These interventions not only contributed to the disaster but also may have made future disasters even more likely. Bernus (1975a) noted that wells not only concentrated livestock but also led to deterioration in land use control:

> These new constructions have often led to a certain anarchy in the exploitation of pasture lands and in the use of space. Once the watering points are put at the disposal of everyone, it becomes impossible for a group of nomads to exercise surveillance over the region it used to control. . .[the policy of water point

> development] has. . .deprived the original occupants--often the owners of wells which they themselves have dug—of the exclusive grazing rights of neighboring pastures.

Thus, this intervention exacerbated the already difficult problem of land use.

Analysis of Herder Perceptions and Values

The physical and socioeconomic environment of the resource user has been described as well as the outcomes of some institutional and behaviorist interventions. Before enumerating recent projects, it would be helpful to look more closely at the herder's perception of the system, since results show that evidently project formulators have not understood their "client populations".

Pastoral Type

The nature of the pastoralists' perception of the system depends largely on which pastoral group is considered. Livestock owning and rearing exist in a multitude of different economies as means to exploit local resources more fully. Thus, livestock are found in many different systems: 1) transhumant herds that follow an annual route according to forage and water availability, and that form the major livelihood of their owners, 2) herds owned by villagers and pastured in the immediate vicinity of the village throughout the year, and 3) herds owned by villagers but which move seasonally great distances from the village. In Chad, certain Arab tribes follow long (600 km) transhumant routes in the east, while near Lake Chad and in the Chari and Logone River Basins, Kanembou, Massa and Arab cattle owned by villagers move much shorter distances throughout the year (INTSH 1972).

Within one pastoral group, not all people are equally wealthy in livestock. In fact, the herds in most groups seem to be concentrated in very few hands. Bonte (cited by Bernus 1975b) found that in one Touareg tribe (transhumants in Niger) 76 percent of the sheep were owned by 6.3 percent of the families. Other studies such as the socio-economic study for the Assale-Serbewel Project (Reyna 1972) show similar concentrations of cattle ownership among village-based livestock owners. Apparently, concentrated individual ownership of livestock was not always the case (Baker, P., 1975), but presently it is clear that within cattle owning groups there are at least two distinct classes of livestock owners.

Herd Values

The rise of livestock ownership among villagers and the apparent division of herd wealth within groups leads to the crucial notion of the utility of livestock. If the functions that livestock perform for their owner could be determined, the resource manager would be more able to suggest substitutes that would be less damaging ecologically or more productive economically.

A great deal has been written on the motivations of pastoralists and their perceptions of livestock. Most of the studies referenced below concentrate on the "pure" pastoralist. Comparatively little is available on the sedentary, mixed herding/farming peoples. This lack of information is unfortunate since the adoption of the livestock innovation by villagers is a major cause of the growth of African livestock populations (Frantz 1975). Since the villagers are not as dependent on their animals as are the "pure" pastoral peoples, they may be more inclined to risk some of the innovations suggested by the resource manager.

Production. A cursory review of the literature shows that livestock are owned for several reasons. Most obvious among these is that livestock produce useful products, milk, butter and to a lesser extent red meat, from otherwise unproductive resources, range fodder plants. The various types of livestock common to the Sahel, camels, cattle, sheep and goats, allow exploitation of different types of forage available at different seasons of the year. The seasonal availability of the forage and water and seasonal risks of livestock disease account for the transhumance of many Sahelian peoples.

Security. Considered in a longer time frame, herds serve as insurance against the variability of rainfall and forage production in the Sahel. During years of good forage production and good harvest, the herds grow rapidly. When bad years occur, the animals can be sold in order to buy the food necessary to insure survival. This adaptation helps explain the widely fluctuating market conditions.

> Cattle are an obvious source of investment, since cattle breed cattle and the animals are readily convertible into almost all other values. All people in the area measure wealth in cows (Horowitz 1972).

It is via the investment in, and the occasional sale of, livestock that the herders pay the bride price and head taxes, the costs of the haj and the religious feasts of the Moslem year. On sheerly economic grounds, investment in cattle herds which grow much faster than any bank account seems to have the greatest survival value.

While herds do provide a measure of security against the vagarities of the environment, some pastoral peoples have substituted other activities that yield more security.

> Employment in the government supported segment of the economy eliminates the need to herd camels as an insurance policy against drought. . .In a very real sense, a marginal niche has been abandoned and a more productive niche developed in the modern sector of the economy (Monad 1975).

Thus, it appears that security is a major motivation of the herder that could move him towards alternative strategies of livelihood.

Social Value. Livestock are the currency so to speak of many social transactions. The payment of livestock to the bride's parents is probably the most obvious example, but loans of cattle to less wealthy relatives and friends serve an important social function. The loans obligate the recipients to the donor and serve to elaborate the social network. Perhaps this too is an adaption to the variability of the environment: he who is rich today may be destitute tomorrow but will be able to collect his debts in order to survive (Baxter 1975; Horowitz 1972). In many cases the value of the social function exceeds the monetary value of the livestock.

> Like the Kababish (transhumant herders of Sudan) what East African pastoralists seek from their herds is "the maximum rate of increase in animal numbers for enhancing social advantage, rather than the optimum rate of offtake for maximizing financial advantage" (Asad, cited by Baxter, 1975).

In some pastoral groups, the role of livestock is not only economic and social, but may also be psychological. Dognin (1975) explains that the Peulh (Fulani) consider their herd as an expression of self. Thomas (1965) gives a moving description of the Dodoth's (Uganda) perception of their herds as wealth itself.

Relationships Between Values. It is usually these descriptions of cattle as wealth that authors seize upon as proof of the impossibility of destocking programs or market incentives in Africa. While it is probably true that destocking as an isolated intervention is not feasible, it is important to realize that its infeasibility stems from its contradictions of a proven existing system of survival. If interventions are to be accepted by pastoralists, it must be demonstrated that the interventions provide a more secure alternative than that of traditional herding with its economic and social security functions.

The tradeoffs between different goals and the risks of innovation might be crucial for the majority of livestock owners who own but a few head. Although they would value a large herd as insurance and social status, they are constrained to a smaller herd that has value as a subsistence economic unit. An interesting possibility is that in Chad women handle the production of dairy products and reap the rewards accruing to the production (Pfister and Rauch 1977). Thus, it seems that there is at least one group within that pastoral society that would be interested in maximizing dairy production. Projects aimed at demonstrating different herd management strategies to those poorer herders and providing some form of insurance if the herders chose to try an innovation, would allow herders the opportunity to assess tradeoffs between their goals.

Recent Entrants to the Livestock Sector. The pure pastoralists are no longer the sole users of the range.

> A major. . .development, often overlooked in discussions of animal husbandry, has been the introduction or expansion of cattle-rearing among horticultural peoples, . . .In addition, cattle ownership has noticeably increased among merchants, contractors, administrators and other business or professional persons, most of whom are town dwellers. Some of this new category of cattle owners have acquired cows. . .as a source of income, since incomes generally can be augmented more quickly than through expanded farming. More frequently, however, this group of cattle-owners build up their stock mainly as a form of social security or a reserve investment (Frantz 1975).

The breakdown in traditional grazing control has allowed exploitation of the range resources by non-pastoral peoples. These peoples' perceptions of livestock may be largely economic. If so, the resource manager might want to concentrate his efforts on this group.

Land Use Control

Working with more production oriented peoples, simply because they are more amenable to livestock interventions that yield monetary results, may lead to a worse resource condition. Recall that at least in some environments, grazing was not always as anarchistic as today. Access to pasture was controlled by ownership of water wells by pastoral groups. Human and animal populations were held in check by natural limiting factors. The concurrent release of limiting factors with the destruction or neutralization of traditional land use control, and the entrance of new resource users had a drastic effect on range condition. The destruction of land use controls allowed the entrance of these new resource users; yet, the establishment of a new and favorable equilibrium requires the re-institution of land use control.

The difficulty in range use control is one of a "common good". Everyone realizes the worth of the good (or the costs of not providing it) but no one is willing to pay for it.

> Fulani herders. . .fully understand the degradation that results from overgrazing, but feel that their own system of land use, among other reasons dissuades them from reducing herd size, since nothing could prevent another herder from moving his cattle on to the improved pasture (Horowitz 1972).

Thus the major difficulty in land use controls is the conversion of a relatively free good to a relatively exclusive good whether that good is land or water. Several factors are involved in this conversion.

Water Points. As many people have noted, forage is indeed free in Africa. Questions posed to herders in terms of land or forage will invariably yield results that indicate that land use controls are infeasible. Yet rangelands can only generally be overexploited if a permanent water source is available. Wells are quite clearly owned by those who dig them. Public wells, such as those dug with foreign aid monies, belong to no one in particular; hence, the overuse of the range occurs around them. Therefore, the desire for new wells might best be handled in a self-help manner so that new wells belong to a particular group. Consequently, they would in essence own the right to use the surrounding range.

Size of Pastoral Unit. If there exists some vestige of traditional land use control that could be reactivated with government support, the populations must be sufficiently integrated so that overuse by one user could be immediately detected by his peers.

Common Action. In a fragmented area such as described around Massakory, where no previous land use control seems to have existed, the institution of land use control would be very difficult since it involves changing the perceptions of all users who have no history of common action. In this case a demonstration of the value of common action is necessary, i.e., the solution is a social, rather than a technical innovation. Such a demonstration is political; yet, to exclude such a project on the basis of involving politics is to ignore the true dimensions of resource use.

Current Projects in Chad

Most livestock projects in Chad are administered through the central government's Ministry of Agricultural and Pastoral Development. The projects fall into each of the four categories suggested by the range use model: information gathering, behaviorist, educational and institutional.

Information gathering

Most of the scientific information pertaining to pastures and livestock in Chad has been gathered and analyzed by the Farcha Laboratory, run by the Institute of Tropical Livestock and Veterinary Medicine (France). While funds are usually available for additional research, the general consensus among Chadian administrators is that sufficient information exists to facilitate project implementation.

Behaviorist

Vaccination programs and the maintenance of the rural veterinary service are the major components of the Livestock Service's funds and personnel are used to support these components.

Several market-oriented interventions are currently being tried. The dairy of the Center for the Modernization of Animal Production is the oldest operating facility. Milk is collected from herd owners in the vicinity of the dairy, processed into pasteurized milk, yogurt and cheese, and sold though the Center's commercial outlet. The Center is strictly production-oriented, and although a study has been made of the effects of the dairy on the lifestyle of the livestock owners (Pfister and Rauch 1977), little is known about the dairy's effect on herd composition and land use.

A second market intervention is the incorporation of all cattle merchants within a national marketing corporation (SOTERA—Chadian Corporation for the Exploitation of Animal Resources) in order to take advantage of economies of scale. The company combines the traditional purchasing system of merchants with a central office that negotiates large supply contracts with neighboring countries. They intend to buy during periods of market glut and hold the animals at one of the former ranches until better market conditions prevail. The increased efficiency is to accrue in part to the herders in the form of better prices for their animals. Yet, the goals of profitable production make it unlikely that a higher price will be offered to the herder by the company, particularly if herders can only deal with a monopolistic firm. This marketing venture only recently began operations, and no studies of its effects are available.

Educational and Institutional

Two projects in Chad and neighboring Northern Cameroon fall into this category—the Assale-Serbewel Project and the Massakory Herder Training Center.

The Assale-Serbewel Project, administered by the Lake Chad Basin Commission, involves the modernization and reorganization of the livestock sector in the Assale Canton of Chad and the adjacent Serbewel Canton of Cameroon. It was begun in the early 70's with the provision of complete veterinary services. The mode of the project was to introduce those innovations most valued by the local people in order to establish a rapport. Once this rapport was established, the project began introducing other innovations: first, a village pharmacy system, a registration of all residents, exclusion of all non-resident cattle and the formation of marketing cooperatives. A project evaluation was written after the first five years of operation, but has not been made available.

The Herder Training Center at Massakory, Chad, had a similar goal, but a different origin. The Ministry of Agriculture established a chain of Agricultural Training Centers throughout the cotton zone of southern Chad. These Centers initially offered technical training and access to agricultural implements. The Centers soon found additional functions, essentially those of animation as mentioned above. The farmers who chose to attend the Centers became catalysts for social change when they returned to their villages.

Project formulators hoped that a similar approach could be used in the northern livestock sector. The Center did not have control of all the pertinent factors in the region; it had no jurisdiction over water wells or veterinary programs as did the Assale-Serbewel project. It did, however, have a greater educational impact. It was not only to offer courses in herd management and health measures but also was to actively solicit the advice of the herders in defining areas of interest. The Center also has land on which to demonstrate the value of range improvements and land use control. The Center only recently began operation, and no evaluation of results is yet available.

Summary

It appears that interventions in the livestock-range sector of the Sahel have largely failed because project formulators did not consider all the impacts of their projects. In future projects, the benefits of the proposed interventions must be clearly demonstrated, and they must be conceived in a fashion that would allow their presentation to the pastoralist as a coherent alternative to his present system of range and livestock use. The non-pecuniary functions of livestock which serve the security needs of the herder and the risks that the herder must take with innovations must not be ignored. Projects with the best chance of success will require a holistic approach, touching not only on technical and economic issues, but also on social structures and the political process.

The Chihuahuan Desert

Description of Milieu

The arid and semi-arid lands of Mexico occupy 41 percent of the country's total surface. The Chihuahuan Desert covers half this area including major portions of the states of Chihuahua, Coahuila, Nuevo Leon, Durango, Zacatecas, and San Luis Potosi, and minor areas of Sonora, Tamaulipas, and Guanajuato (Henrickson and Straw 1976). This region occupies the plateau between the Sierra Madre Occidental and the Sierra Madre Oriental in north central Mexico and extends into the United States occurring in Arizona, New Mexico and Texas.

Abiotic

The Chihuahuan Desert has two general climatic zones, the steppe and the desert which define the semi-arid and arid zones, respectively (Garcia 1978). Annual precipitation is 350 mm or less and occurs mainly in the mid- and late summer months as isolated storms or as a consequence of cyclonic disturbances in the Pacific or Gulf of Mexico. The majority of rainfall occurs in the summer, and a drought period occurs between November and April (Marroquin et al. 1964). The summer rains develop from warm, moist air masses which originate in the Gulf of Mexico (Tamayo 1976). Precipitation is highly variable in time and space. The mean maximum temperature of July, the hottest month, ranges from 32 to 34°C in the southernmost part and increases to 40°C in the north (CETENAL 1970). January, the coldest month, has mean minimum temperatures ranging from 2 to 4°C.

The soil order most common in the region is the aridisol. This represents mineral soils that have no water available to plants for long periods, and soil layers dry throughout the rest of the year. A common feature of these soils is the presence of a layer of carbonate accumulation or caliche resulting from a lack of or very light leaching (Buol et al. 1973).

Biotic

The vegetation of the area is highly diverse. Twelve different vegetation types were classified for Coahuila alone (Hernandez 1970). However, the more extensive grazing land corresponds to the Desert Scrub (microphyllous inerm) dominated by the species *Larrea tridentata* (creosotebush) and *Flourensia cernua* (tarbush). According to Gonzalez (1972) this vegetation unit, found in the open valleys and mesas, occupies approximately 10 million hectares. The most common forage-producing species are annual grasses such as *Aristida adscencionis*, *Chloris virgata*, *Bouteloua barbata* and *Enneapogon desvauxii*; and some perennial grasses like *Hilaria mutica*, *Muhlenbergia repens*, and *Muhlenbergia porteri*. The last are observed in the bottomlands where additional moisture comes from upslope runoff. An inventory carried out in the early 1960's showed that 86 percent of this vegetation type is grazed yearlong while the rest is used for seasonal grazing of steers and heifers.

Above this vegetation type, in the altitudinal gradient, is the Desert Scrub (rosette-forming leaves) characterized by several shrubby species of the genuses Agave and Yucca. The production of forage is higher and comes mainly from the following perennial grasses: *Bouteloua breviseta*, *B. gracilis*, *B. curtipendula*, and *Heteropogon contortus*. Because of the lack of watering points, this community is used seasonally.

In the playas, halophytic shrubs and grasses are found. An important halophyte association is the Atriplex-Prosopis-Sporobolus association (Gonzalez 1972). Major species are *Atriplex canescens*, *A. nuttelli*, *Prosopis juliflora*, *Sporobolus airoides*, *Panicum havardii*, and *S. plexuosus*.

The area supports a scarce population of big game including deer, cougar and lynx. Other animals of regional interest are hares, rabbits, rattlesnakes, pigeons, racoons and coyotes. Game species provide limited sources of income but provide a recreational activity for urban people.

Economic

Except for well-defined irrigation districts, the rural population has three main occupations: 1) rain-fed farming of staple-food crops, 2) gathering and extraction of native plant products, and 3) open-range livestock husbandry. The subsistence agricultural activities, as a result of low and erratic rainfall, are highly risky operations; on the average, crops are lost in three out of five years. Farming is carried out with low levels of mechanization with most work being done by animal traction implements and hand labor. Cultivation and harvest of crops are almost entirely dependent on hand labor, except for the early plant growing period when it is possible to utilize draft animals. Maize and beans comprise the majority of the crops, but wheat, barley, and vegetables are also planted.

During the non-farming period some seasonal part-time activities exist such as the gathering, extracting, and selling of native plant products including fruits, fibre, wax, and other products. The most important plants are lechugilla (*Agave lecheguilla*) and palmas (*Yucca filifera* and *Y. carnerosana*) for extracting ixtle fibre, and candelilla (*Euphorbia anvisiphyllitica*) for extracting wax. This activity often provides the sole source of income during annual dry periods.

Cattle, goats and sheep use the shrub-grass communities in the region. Three forms of livestock raising can be distinguished: 1) patio or small livestock, 2) mixed nomadic livestock, and 3) range livestock. The patio livestock comprises all of domestic animals species—hogs, chickens, turkey, rabbits, ducks, etc., that are raised in the yards or patios of the individual householders. Housewives and children normally take care of the animals and feed them with food waste, wild vegetables, hay and grains produced by the householders.

The mixed nomadic livestock includes the family herds of cattle, sheep, goats and horses that graze near villages, fallow farms, and aftermath crops. These animals are also provided with hay and silage in the patios.

Range livestock raising consists mainly of cattle grazing permanently and freely in the rangelands of the community. Herds are generally owned by a small group of peasants who each pay a grazing fee to the community's authorities. Elements basic for complete use of the range resources--such as fences, watering points, salt troughs, and others—are lacking.

About 90 percent of the active population is engaged in primary activities generally for local consumption (Fernandez 1975). As a consequence, the tenants are very much restricted in their accumulation of working capital for improvements or to finance modernization projects.

Social

The average social and economic conditions of peasants in the arid and semi-arid zones of Mexico are the poorest among the country's population. Whetten (1948) stated that the living conditions of rural people in Mexico were just as their ancestors had lived with inadequate nutrition and educational levels and without any faith in government officials.

The rural communities are widely scattered, and a high proportion have low populations. Access to these small communities is through unpaved roads which are almost impassable during the rainy season. In 1970 the total population resided in 21,280 towns or villages, distributed as follows: 62 percent had less than 100 inhabitants, 27 percent had 100-500 people and 11 percent had more than 500 people. This situation has limited the introduction of the basic public services at reasonable costs. De Vries (1962) notes that: ". . .the fact that ejidatarios live in scattered hamlets has hampered the development of any social facilities."

In most instances the local villages present an internal duality with respect to the ownership of production factors. On one hand, a small number of landholders monopolize most of the local resources, and by exerting economic pressure on the less affluent tenants, control the local economy (Guzman et al. 1978). On the other hand, most people have little choice of farming systems and are customarily engaged in operations that produce low outputs per hectare, such as livestock raising and gathering native plants.

In general the region suffers from a highly pernicious phenomenon that is detrimental to social and economic development: the "minifundia" (Manzanilla 1969). This problem is closely associated with the land tenure system in Mexico. The legal forms of land tenure for non-urban areas are the Private Property and the Ejido. The first is a type of land subject to limits in size. For irrigated agriculture or its equivalent, 100 hectares is the limit; for cotton and fruit orchards the limits are 150 and 300 acres, respectively. For livestock raising, the limit is dependent on the carrying capacity of the range, but no more than an area sufficient to support 500 animal units is allowed.

The Ejido institution of land ownership refers to an agrarian community which holds land in accordance with the agrarian laws resulting from the revolution of 1910. The law provides that each ejidatario (a member of the Ejido) is to receive a parcel no larger than eight hectares for farming. The rangeland is commonly used by the Ejido's members without any special restrictions on the extent of use. Presently the Ejido structure allows for community-owned projects which are generally supported in part by government institutions. De Landa (1976) considers that the present land tenure system inhibits livestock development projects. He affirms that the Ejido lands comprise approximately 43 percent of the land, and that they are inadequate for profitable livestock raising. The private sector owns the remaining 57 percent but the land is in the hands of a few people.

Interventions

The communal land tenure system in Mexico is not a new institution, having been held by the native indian tribes of ancient Mexico. A brief description of that situation is given by Blanco (1955):

> . . .pre-hispanic codices and the narratives of the Spanish missionaries reveal that among the native tribes—specially the Aztecs—occupying the central plateau before the Spanish conquistadores arrived, the land was distributed in five groups. The best were the lands owned by the royal family. Next best were the properties of the nobility, then those that belonged to the temples, then the army lands. Those of the rest of population were, of course, the poorest and smallest. . .title [of the communal lands] was vested in the community, although the families that worked them controlled the produce. . .

After the Spanish army conquered the Indian tribes, the land tenure system showed a radical change. Under the Spanish domination, the ownership of colonial lands was divided into three major categories. These major groups were: 1) the private property of high government officials and the soldiers of the conquering army, 2) the property of the native communities, granted by special royal decrees (Blanco 1955). The last category is the origin of the Ejido. The word "Ejido" is derived from the Latin "exitus" which means located out of town. Some characteristics of landholding during the Spanish domination in Mexico are outlined by Humphreys (1946):

> . . .in feudal Spain the great estate was the normal landholding, but villages and towns held title to common land--the ejido--without their gates. . .villages and towns were to have the Ejidos, and the Ejidoes were not, as in Spain, simply the waste lands at the exit of the village, but the whole of the [traditionally indian] communal agricultural land. . .

Brand (1961), in his historical review of the range cattle industry in northern Mexico, emphasizes the prosperous existence of many latifundio (large estates) chiefly dedicated to cattle raising activities. This industry had its rise and fall. From 1832 to 1884 cattle ranching declined because of the frequent Indian raids. From 1884 to 1910, the cattle industry increased; finally, the revolution period from 1910 to 1923 brought the range cattle business to an end.

According to McBride (1923), the war for independence (1810-1821) did not affect the land tenure pattern itself because the large estates formerly owned by Spaniards had now passed into possession of native-born Mexicans, either creoles or mestizos. Land monopoly steadily increased in the following years, and by 1910, 95 percent of the people who worked the land did not own it.

This situation caused a revolution which was mainly directed against the latifundia system, and the most popular battle cry was that of Zapata: "the land belongs to those who work it." After the triumph of the revolution, several plans were made to reorganize and redistribute the land. An Ejido could be organized when a group of at least twenty peasants asked the government for land. If they were able to prove that their community owned the land either during the time of the Aztecs or under the Spanish domination, the government returned it at once. If they had never owned land, the government allocated land from the neighboring large estates.

Presently the Ejidos play a very important role in the agro-pastoral development of the area.

> . . .today the better use of the ejido, either in modernized communal farming, or by subdivision to peasant small-holdings run as family farms, has been described as "Mexico's way out", and the country's main hope of raising rural standards of living. . .(Watson 1967).

However, land tenure reform was essentially social in nature, which amounted to an almost entire neglect of the technical aspects related to the planning, management, and proper utilization of the land. Rangelands were subjected to immoderate exploitation which impaired their productivity. Further deterioration resulted from the plowing of extensive shrubgrass communities for rainfed farming (Aguirre 1973).

Livestock, as a Spanish legacy, brought several cultural elements:

1. The Mesta, a social system of investments' monopoly, lawful rights, and exclusiveness of inheritage.

2. A concept of extensive livestock exploitation.

3. Exclusive attention to domestic animals and an attitude of indifference to the rangeland resources.

4. The use of the number of animals as a yardstick of the wealth of the range livestock (Reyna 1958).

The present situation in the arid and semi-arid rangelands is summarized by Hernandez (1970): 1) low levels of technology, 2) low levels of productivity, 3) overstocking, 4) incipient efforts at range and livestock improvement, and 5) slight attempts at range management research.

The over-exploitation of the rangelands can be analyzed from two perspectives, dividing the pastoralist in private owners and ejidatarios. Most of private ranchers tend to overgraze the range because normally their land is unlawfully owned and disguised under different names of relatives, friends, subordinates, and others (Roldan and Treuba 1978). For this reason they are constantly intimidated by landless peasants petitioners of land before government authorities. The Ejido rangelands are collectively owned by the entire community, but livestock are individually owned. Few owners try to obtain the maximum possible return from the land pushing the range resources beyond their carrying capacity.

Analysis of Perceptions and Values

Implementors of range development projects in the Chihuahuan Desert have not been concerned with equity of benefits. It is suggested that projects include some societal alternatives to distribute benefits more evenly among the people. This aspect was clearly pointed out by Manzanilla (1969) when discussing the role of sociologists in agrarian reform:

> . . .the sociologists's task, that analyzes the process of specialization, integration and adoption of man in the new agrarian structure, has been underestimated. It seems that specialists, politicians and economists only consider the land, capital, production and marketing as essentials in the agricultural process, forgetting that between land and the other factors is situated the man and his organization.

Moreover, the previous knowledge of the people's peculiar patterns of social organization must be matched with the development of efficient agricultural extension activities for the diffusion of new technology, and planning of development projects in rural areas.

> . . .this bespeakes the necessity for effective technical guidance so that he [the peasant] may acquire the more efficient agricultural practices. Much of this guidance, to be effective, must be of a demonstrative nature. It is necessary to demonstrate to him the superiority of the more efficient technique with concrete illustrations that he can readily understand. . .the challenge will be to devise programs that will fit the needs of the local inhabitants; that will gradually lead them to accept more efficient techniques . . . (Whetten 1948).

The major prerequisite for a range improvement program is obtaining the basic information on the people's standards and means of living, social customs and relationships, traditions, attitudes, beliefs, and main occupations. And as it was stated by Dickson (1957), extreme care must be kept ". effort from the beginning. . ."

It is evident that to succeed in a particular development strategy, it is necessary to demonstrate first that the local pattern can be improved. For that purpose, it is of prime importance to design a scheme to genuinely identify the felt needs, articulate them as a problem, search for solutions, determine alternatives, and implement them to reduce their effects (Havelock 1969). The process of technology adoption will be facilitated, in a large measure, by the identification and the recognition of the needs and problems of the people.

Current Approaches

Information Gathering

In 1965, the federal government through the Secretary of Agriculture and Livestock created a technical commission to determine the carrying capacity of the country's rangelands. The fundamental goal was to formulate a technical basis to define the area of land sufficient to support 500 animal units. By 1975, 83 vegetation types and 1400 range sites had been classified (Martinez 1975). This important data base constitutes an essential element for the planning and development of the range resources of the country.

A preliminary analysis of the inventory showed that approximately 37.5 million hectares of arid and semi-arid rangelands were degraded and that 17 to 53 hectares were required per animal unit year (Martinez and Maldonado 1973). An earlier survey conducted in the north-central states indicated that only 25 percent of the range was in good to excellent range condition (CFAN-CID 1965).

Recently, a more integrative approach has been applied in a region of the Chihuahuan Desert in northeast Zacatecas (Riveros et al. 1979b). In addition to the evaluation of the land resources, the social structure, infrastructure, and exogenous variables have been included in the analysis. This information base along with the analysis of research results on land use management alternatives and potential productivity of the resources was used to elaborate a theoretical approximation of the productive potential of the area and an organizational alternative of resource utilization that supposedly can result in a more optimal state of the region.

Behaviorist

Many attempts have been made to solve the critical economic conditions of the area's people. Unfortunately, few have been recorded in the available literature. A recent major effort was conducted in the Candelillera Zone, a region embracing all the wax-producing Ejidos. A special fund from the National Association of Importers and Distributors of Parafin was created to promote the diversification of production activities among the ejidos. Such a diversification was important to reduce the economic dependency of Ejidos on the gathering of candelilla native plants for the extraction of wax.

A technical committee was organized for the allocation of funds among the Ejidos and included representatives of the Association of Importers and Distributors of Parafin, government officials, and ejidatarios. The projects varied according to the Ejidos' particular needs but usually included livestock and domestic water developments, land clearing and deep tillage, environmental sanitation planning, range reseeding, introduction of poultry yards, and improvements in the rural housing.

Guzman et al. (1978) analyzed four of the 39 wax-producing Ejidos in central-oriental Coahuila. A great proportion of the livestock, trade, vehicles and machinery was controlled by a handful of individuals who obtained the greatest benefit from the projects. It is evident that benefit distribution is still a problem.

From these experiences, all the projects carried out during the period from 1975 to 1977 ha the support of previous surveys which helped to reduce ongoing project improvisations. Projec were oriented to alleviate the needs of ejidatarios according to the results of the surveys. T activities started only after several meetings with Ejido assemblies in which the projects wer fully discussed.

Summary

From the present analysis it may be concluded that the Ejido as an organizational unit mus contain a social-cultural status and technological level in accord to the natural resource system The large estates of the pre-revolution era have been converted into "mini-estates". The Ejido ha been assisted by a bureaucratic structure with little understanding of the problems of the Ejido Temporal and impromptu solutions have often contributed to less efficient patterns of productio and resulted in less organization of the people. It seems of greater value to work with th population's intermediate strata, because they seem to represent more truly the interests of th well-to-do and the less affluent sectors of the Ejidos. Generally, the Ejido leaders originate fro the intermediate strata and they foster change in the community.

The Navajo

The Navajo consititute a society somewhat different from the others mentioned in this pape for they are a nation fighting to survive within and to integrate into a society which is basical very unlike their own.

In order to study rangeland problems on the Navajo reservation it is important to have general understanding of factors that have helped to form their society. The Navajo have integrate bits and pieces of many peoples cultures into their own, so that although strictly Navajo they ar strongly affected by outside influences.

Since they first encountered white men, the Navajo have been fighting to retain the identity as well as to survive. Downs (1964) discussed in depth the problems of integrating, acculturating, the Navajo into American society and cites House Report Number 2503 (1958) in whic acculturation was defined as the gradual change of indians into "Americans" with the disappearanc of indian culture being the expected outcome of the process.

At present the Navajo people are in serious trouble both physically and financially. The land is greatly overcrowded, and their soils and vegetation have been depleted. However, the cannot be held completely responsible for these conditions since the imposition of white ways up their own and their confinement to a limited space may have created a majority of their curren problems.

To date, very few documented range-related projects have been undertaken on Navajo land those projects available for reference will be discussed here. General themes which have been wove into the description of each of these projects is that the Navajo are a people very different fro the white people surrounding them, and that it is difficult for them to accept white peoples answers to their problems. The Navajo are a very proud people. In their language the word f themselves, *dine*, means "the people". Historically one of the basic problems confronting them ha been that they have not been treated as such.

Abiotic

"The Navajo Reservation is located on the Colorado River Plateau of the Intermonta Division of the United States and covers portions of three states: northeastern Arizona northwestern New Mexico, and southwestern Utah," (Leviness and Ogden 1974). Although the Nava were originally allocated only 3,500,000 acres, the size of their reservation rapidly increased its present size of approximately 15,000,000 acres, of which 65 percent are in Arizona, 27 percen are in New Mexico, and 8 percent are in Utah.

There are four general types of topography on the Navajo Reservation: 1) flat alluvial valleys, 2) broad rolling upland plains, 3) rugged tablelands, and 4) mountains. Valleys are often wide and flat and tend to be broken by flat-topped mesas, buttes, and steep spires (Leviness and Ogden 1974). Elevations range from 1,200 meters in the valleys and 1,800 meters in the plains to as high as 3,000 meters in the mountains.

Precipitation normally follows a split-season distribution pattern as is characteristic of most of the Southwestern United States (Leviness and Ogden 1974). During the summer months about 50 percent of the precipitation falls in heavy thunderstorms; during the rest of the year gentle precipitation is the rule.

Three distinct climates are characteristic of the area. A warm desert climate prevails on approximately 50 percent of the area, the middle elevation has a "steppe" climate, and the higher elevations have a cold, mountainous climate. Rainfall averages only 20 cm over the entire area, so agriculture is not really favorable anywhere except where irrigation water is available. Because "high temperature during the summer and sub-zero weather during the winter, high winds, frequent sand storms, and high evaporation rates are characteristic," (Kluckholm 1962) the Navajo live in an area in which successful agricultural existence is extremely difficult.

The soils of the area were formed primarily from sandstone and limestone parent material (Leviness and Ogden 1974). It is generally believed that the productivity of the soils has decreased by as much as 50 percent since 1868. Kluckholm (1962) states that in 1961 15 percent of the total area was worthless for plant production, 23 percent was in poor condition, 29 percent was in fair condition, 22 percent was in good condition, and 11 percent was in excellent condition.

Upland soils are sandy to sandy loams and variable in depth with sand dunes and clay "badlands" common. Floodplain soils are deep loams and clay loams which are often highly productive but may be high in salts making plant re-establishment difficult (Leviness and Ogden 1974).

Biotic

A wide variety of vegetation types occur on the Navajo grazing lands. Leviness and Ogden (1974) mention the following plant association: sagebrush, blackbrush, shadscale, shortgrass, pinyon-juniper, and ponderosa pine woodlands. Under good conditions these vegetation types are all capable of supporting healthy livestock herds; however, limiting climatic and topographic characteristics create a fragile balance between animal numbers and vegetative productivty on Navajo land.

Socioeconomic

The Navajo live on some of the poorest lands in the United States and most can barely survive as herders and farmers; yet, they are very closely tied to both their land and their animals. Many young people are now educated enough to make a living off of the reservation but large numbers of them choose to stay behind because "I was born here and I like it here" (Downs 1964).

The Navajo are Apachean indians who migrated from Canada to the southwestern portion of what is now the United States sometime between 1000 and 1500 A.D. There they established a society based upon skills as hunters and gatherers. Shortly thereafter they came in contact with other peoples of the area and acquired the farming and weaving skills which would eventually lead to their strong bond with the land and with the area in which they lived. In fact, in their own tongue the word "Navajo" means "large areas of cultivated land" (Kluckholm 1962).

The first known written reference to "the people" was in the report of a Franciscan missionary in 1626. By that time the Navajo had become accomplished agriculturalists and no longer were a migratory society (Kluckholm 1962). Agriculture was then the basic economic pursuit but the introduction of sheep, goats, horses, and cattle by the Spaniards soon changed that. Livestock opened up totally new avenues for the Navajo people and allowed them to advance above and beyond other Apachean peoples. Their economy soon came to be based upon animals, with wool, mohair, hides and woolen textiles providing a steady source of exchangeable income for the first time in Navajo history. "Livestock formed the basis for a transition to a capitalistic economy, with new goals for individuals and for family groups, a new system of social stratification and prestige hierarchy, an altered set of values," (Kluckholm 1962).

With the introduction of horses the Navajo became more mobile; they were able to control larger areas and to raid other tribes for stock and slaves (Aberle 1978).

During the years 1626–1846 major alterations in the lives of the people occurred. Without their knowledge the entire Navajo lifestyle was being changed, and they were beginning to become aliens on their own land.

Beginning in 1846 the Navajo were under American rule. American troops continuously ravaged the Navajo people destroying their pride and homes as they cleared the way for settlers moving west. Years of tragedy climaxed with the long imposed walk to and imprisonment at Fort Sumner in 1864. The Navajo had been defeated, and 8000 of them would spend the next four years in captivity (Aberle 1978). When it became apparent that the Navajo could be kept in captivity no longer, they were allowed to return to a small portion of their original land holdings and were given a minimal number of livestock to raise.

On returning to the reservation the Navajo were allotted only 15,000 sheep, 2,000 goats, and 30,000 horses. However, livestock were still used as the primary measure of Navajo wealth and so they enthusiastically attacked the problem of increasing livestock numbers. "When the Navajo culture is examined. . .we see that the acceptance of livestock as a subsistence base in the seventeenth century was a crucial aid shaping all subsequent Navajo history and culture. . .(Downs 1964). By 1930, herds had increased to approximately 1,300,000 sheep and goats and 75,000 horses, and the human population had increased to the extent that all of the people could no longer be supported by the land. In the 1930's the Phelps Stokes Fund (1939) sponsored a study which estimated that the carrying capacity of the land was only 600,000 sheep. Many of the people were living off government funds, and the quality of life was very poor.

Interactions between the American government and the Navajo people are officially channeled through the Bureau of Indian Affiars, also known as the Navajo Agency. The BIA is responsible for all aspects of reservation life from the economic and social welfare of the people to their health; as such, it is unique among governmental agencies in that it is concerned with a broad range of areas.

In actuality, however, it has historically been the trader who has been responsible for the introduction of new elements into Navajo life. The wants of the people used to be very few, but with more and more intermingling with white society the Navajo have come to require many non-reservation articles. "The trader allowed the Navajo to remain on-reservation and yet obtain those items of white culture that they desired (Downs 1964).

Interventions

In the 1930's the federal government instituted a number of programs aimed at improving the condition of Navajo rangeland, which were aimed at increasing the quality of Navajo life.

At that time nearly 12 percent of their total land area could have been considered complete waste. Thirty percent of the land would support less than one sheep per 50 acres. Seventeen percent of the land would support only one sheep on every 17-25 acres, and a mere 29 percent of the land would support a sheep on less than 16 acres. The range had deteriorated to the point where more than 75 percent of the productive topsoil had been removed from 10 percent of the area (Kluckholm 1962).

Resource and Social Programs

Better breeding stock were pruchased and offered for individual use in an attempt to increase the quality of the herds. Soil programs were initiated in an attempt to control erosion but failed because of the Navajo belief that nature is the Supreme Power and that is is therefore presumptuous of man to try to control her. Health programs also were initiated, but they too failed because of the Navajo belief that the body should be treated as a whole and that individual parts should not be treated separately (Kluckholm 1962).

Educational Programs .

The educational advancement program began at the same time as the stock reduction program. This program was aimed at educating both the young and the old in order to prepare them for non-lievstock oriented livestyles and to introduce them to "better" livestock handling techniques.

Like many other federal programs, the schooling began without Navajo consent. Children were sent to boarding schools away from the reservation where they were broken of many Navajo habits, and thus they were prepared neither for life on the reservation nor away from it. Soon government officials realized that they must educate the Navajo to be Navajo. Schools were built on the reservation, Navajo teachers were used, and the program began to be accepted. This made educational programs one of the few to be successful in the long run.

Stock Reduction

The most consequential programs were the stock reductions begun in 1933. The reduction was voluntary in 1933, 1934 and 1935; a planned and imposed reduction began in 1937 (Aberle 1978). Federal funds were made available for the purchase of surplus stock, and for the employment of Navajos in conservation work so as to supplement their loss of livestock-related income.

There was a minimum of community involvement in the reduction program (Aberle 1978). The tribal council was asked to carry out the reduction but was not asked to participate in its formulation.

> Beginning in 1933, range surveys laid the basis for systematic reduction. The reservation was divided into land management units, or districts, their carrying capacity estimated, and a permit system devised that required reduction of the districts herds to carrying capacity by reducing large herds and freezing smaller ones at current herd size (Aberle 1978).

Although the program was originally aimed at reducing the size of large herds, all herds were reduced by similar percentages. This gave large livestock holders the opportunity to cull their herds while driving many smaller herders out of business.

By 1945 livestock reduction to below carrying capacity had been accomplished and per capita livestock income rose by 7 percent. However, the Navajos were not in the livestock business in the same way that nearby white ranchers were. Navajos ran a household economy, using livestock for exchange at the trading post, for food, and for social purposes; livestock reduction destroyed that economy. Navajos had less protein overall, and they had fewer livestock to give away at social occasions. More and more Navajo were forced to become wage-workers, which involved changing their entire way of life. Few Navajo gave up owning livestock altogether:

Reasons for Failure

With regard to the model proposed in Section I, most of the failures of range projects can be attributed to misunderstanding of: 1) the system components, or 2) interactions between components of the range resource use system.

Project formulators have often misunderstood or ignored goals and perceptions of livestock owners; they have designed projects that would increase livestock quality or production, while the pastoralist has generally been interested in animal numbers and the security that big herds afford. The smaller herd usually envisioned in range management plans to provide for proper range use would be a better survival strategy only if land use controls existed--an innovation that would require the cooperation of all resource users and the implementation of institutional changes.

The need to account for the social dimension of cooperation between actors has often been ignored, typifying the second general source of system failure: misunderstanding the interactions between system components. Within this category falls one well-known example: the failure of water point installation to increase pastoral welfare. In this case, technology has altered ecological interactions to the point that only food supply—the ultimate limiting factor--is important. Social considerations often hinder any treatment of this limiting factor; therefore, attempts to deal with these considerations simply by the use of technology leaves the system vulnerable to further dysfunctions and future disasters.

Critical Factors in Exchange and Development

Project Design

Orientation

Since our analysis has highlighted the present importance of social factors, range projects should explicitly recognize and deal with those factors. Often it would seem that social factors are much more critical than technical considerations. Of course, technology serves an important function in that its quick results and visibility facilitate the establishment of a rapport with the local population. However in the long run, emphasizing land use practices, interactions between groups and control within groups may be more important aspects related to the transfer and diffusion of technology.

Duration

Since social interactions are considerably more difficult to determine and alter than are technical means of production, project formulators should conceive of projects as long-term commitments to the local society. Permanent results cannot be expected in less than 10 to 15 years, and a more realistic figure might be that of a generation. Social change is a lengthy process and project formulators, as well as funding agencies, should recognize this. However, short-term incentives must be considered so that the project may be attractive and more easily accepted by the beneficiaries.

Local Conditions

Since our analysis has defined local practices as selected means of exploiting local resources, projects should attempt to specify and use the particular ecological and sociological conditions characteristic of the project zone. Rather than viewing the region merely as a site with varying suitability for given technologies, project formulators should allow regional conditions to suggest directions to be taken. For instance where a form of land use control does exist, projects might consider strengthening that control structure while providing some means of insuring distributive justice. A diverse region such as a mountainous or plateau province might provide a better mix of resources throughout the course of the year than would a plains environment, thus allowing for a more sedentary population and easier regulation of land use. Therefore, regional characteristics rather than possible innovations should be the project's point of departure.

Project Implementation

Public Involvement

It is a truism, often forgotten, that people are a region's most important resource. Social change is a means by which the "human capital" of a region can be more fully developed. If the orientation of a project is that of social change, the local population must be involved in virtually all aspects of operation. It is particularly important that the local public be given the opportunity to suggest or modify innovations, whether technical or social. The true feasibility of such innovations can then be quickly determined and, more importantly, the nature of the local evaluating and decision-making process can be seen in action.

Project Personnel

Critical to the success of any project are the people that staff it. Since our analysis points to social change as the predominant factor in the improvement of range resource use, personnel must concern themselves with this dimension even if their professional specialty is technical. In all cases project personnel should consider themselves to be change agents, rather than mere conduits for technical transfer. Factors such as personal comportment, attitudes toward local people, and the ability to adapt to and integrate experiences from a new environment may be more important than technical skills.

Local Power Structures

Much extension literature recognizes the importance of leaders in the acceptance of innovations. Whenever the innovation is in fact a change in the social structure, it is necessary to identify what Friedmann (1969) calls the "societal guidance system"--those individuals and institutions that guide the evolution of a society. The societal guidance system might include traditional chiefs and their councils, religious leaders, important merchants and so on. Working with this traditional power structure increases the likelihood of a significant social change, since personnel will be seen as supportive of, rather than antagonistic toward, traditional mores.

Demonstration and Risk

Returning to the characterization of traditional resource use as a survival strategy, local people are not likely to accept an innovation unless it can be clearly demonstrated as superior to traditional means. While demonstrating the value of a technical innovation may be relatively easy, the demonstration of the value of a social change may be considerably more difficult, requiring time, ingenuity in design, appropriate documentation and frequent consultation with the local people.

It is also important to remember that an innovation successful in one region may not be successful in another. Preliminary studies can tell us only approximate probabilities of success. An on-the-site trial is necessary to show the value of the innovation in any particular region; however, it is unreasonable to expect local people to risk their meager personal resources for such experimentation. Therefore, a project manager should assume this risk-taking experimentation or provide some means of insurance to those who are likely to participate in any experiment.

The Foregin Technical Expert

The above recommendations also apply to the technician of the foreign aid agency except that he should view as this target population his host country counterparts. In this case the social/ecological conception of resource use may be the appropriate innovation he wishes to impart to his counterpart. Thus, he must orient his activities around the transfer of this concept. He must deal seriously with the experiences and attitudes of his counterparts, integrating these with his own experiences, while remaining aware of his own basic role of change agent within the professional community to which he and his host country counterparts belong.

The foreign technical expert should consider his host country counterparts as the legitimate interpreters of the local populations. Attempts to bypass the local professional power structure can quickly eliminate any possibilities of future cooperation. For example, although veterinary programs may in fact be inimical to the solution of a long-term problem, short-term funding of these projects may help establish important professional rapport with the local agency.

On the other hand, even if the foreign expert does have enough influence, he must still seek ways to demonstrate that the projects he proposes can yield significant results. Furthermore, he must be willing to commit the funds necessary to demonstrate the value of his project. Few local governments have resources so vast that they can allocate their funds to projects of unknown value.

Social Change and Experimentation

Change is inherent in human societies if only because of natural increases in population. The rate of change in some traditional societies has been accelerated due to a cultural differential created by colonialism or other forms of exposure to the West. In some cases the traditional equilibrium has been drastically altered if not destroyed. A new equilibrium will eventually be established, but it may not necessarily be one which would be considered beneficial.

Development can be viewed as a more or less conscious search for a new dynamic equilibrium, one that will yield higher returns over the long run than could the traditional system. Development is more or less directed social change. Yet in terms of the present model, it is nearly impossible to determine whether a conscious social change will bring us close to the desired state of affairs. This, along with the limited number of how-to-do prescriptions, places rural development actions in a no-man's-land in the research arena. A range development project must, therefore, be viewed as a learning process which should be subjected to critical scientific analysis in which the actions are inserted in a theoretical framework.

Experimentation should be done with procedures and results visible to the local population whereby social or technical innovations could be tested for their effects. Projects designed and implemented using this sense of experimentation and adaptation would provide one method for peaceful and positive rural change. In addition, such projects would constitute an invaluable vehicle for the promotion of knowledge concerning applied strategies for directed social change.

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DEVELOPMENTAL PLANNING AND THE ENVIRONMENT

by Richard E. Saunier

I. Introduction

The purpose of this unit is to present a justification and a methodology for including "environmental" work in development planning efforts. First, this requires a look at the foundation upon which development and planning exist because the foundation for including environmental work is no different. Second, it requires a few definitions in order to rid ourselves of some misconceptions. In addition, we will take a rapid look at some general guidelines for planning, and then outline a methodology itself.

Development has been defined as the "application of human, financial, living and non-living resources, in order to satisfy human needs and improve the quality of life." To make this definition a bit more useful, one must have some idea of what is meant by the phrase "to satisfy human needs and improve the quality of life." What are those human needs? Table 1 lists several categories related to human needs and life quality.

Both the needs and their satisfaction will vary between and within populations as well as between individuals and even in the same individual over time. The items in this list appear to be basic; a minimum of each is needed for anything like human life to continue; improvement on them is to improve the quality of life. Successful effort at improvement is what we should mean by development and this in turn indicates some guidelines as to how one should go about development planning. Explicit in the definition of development is that the "quality of life" should be improved. That leaves aside any number of projects that have been called developmental which, in fact, have not been developmental. We ought to be very jealous of the word development and make sure that it means "change to improve quality of life" and not just "change."

But where does "environment" fit in? The question asked by many, in developed and developing countries alike, is "why don't the environmentalists leave us alone so that we can get on with the process of development?" Although perhaps once valid, it is now a non-question because it has been defined out of existence. That is, the environmental/developmental debate was raised as an issue because a large number of people began using words not clearly understood by the hearer nor for that matter by the speaker. One of these, of course, is development. Others are: environment, environmental impact and environmentalist. Also, because it will appear in one way or another in these definitions, we need to define ecosystem.

An ecosystem is a geographic unit or organization which comprises an interacting community of living organisms and its non-living environment. Since each ecosystem is somewhat arbitrarily defined, there are innumerable ecosystems in the world. A large ecosystem, such as a river basin, contains many other ecosystems (forests, lakes, rivers, farms, pastures and cities). There is a physical portion which influences and is influenced by the activities of the biological portion; and there are a large number of processes which condition the interaction between components.

It is important to remember at this point that ecosystems are characterized by both "structure" and "function." The structure of an ecosystem includes, for example, the

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protection by making an ecological reserve. Table 3 gives some of these alternatives. Note that the impacts may occur both in the present and in the future and on the "resource" being developed as well as on the other resources. They also may be positive or negative.

Since these goods and services are eventually translated into human welfare they can be assigned to socio-economic sectors. This gives a second important definition of environmental impact which is the net change in man's well-being brought about by man's activities in those ecosystems that surround and support him. The impact may be positive or negative and is generally described by the affected poulation or sector. In negative terms, it is one sector or subsector (or even the same sector) playing havoc with another sector or subsector. For example, following the Table of Economic Sectors as defined by the United Nations (Table 4), a declining fisheries production caused by erosion and sedimentation as a result of timber harvesting activities is Sector 1.2 against Sector 1.3; air contamination from a petrochemical complex that causes health problems in the surrounding population is Sector 3.5 against Section 9.3.3; the problem of water allocation between hydroelectricity and irrigation is a problem between Sectors 1.1 and 4.2. Nearly any negative environmental impact can be defined as a problem between and within sectors.

What is common to the vast majority of the negative environmental impacts is that the quality of the affected human population has been, in some significant way, decreased -- the very antithesis of what development is about. Given the above definitions, the debate is indeed between development and nondevelopment but not in the context of development versus environment.

This then brings us to a definition of enviromentalist. It is a word replete with misconception. No doubt, many who call themselves environmentalists are not, and many who do not call themselves environmentalists very much fit that category. To begin with, an environmentalist is someone who has a broad view. That does not necessarily mean broad knowledge. A specialist may or may not be an environmentalist. There are foresters and ornithologists who are not environmentalists; there are engineers and economists who are. What makes an environmentalist is an understanding that the environment extends well beyond the contents of any one sector or discipline, and that the whole is at least different from, if not greater than, the sum of its parts. An environmentalist is one who acknowledges that important interactions and interrelationships exist in the environment and who therefore works and acts in an integrated and integrative fashion. What this means is that any member of a planning team can be an environmentalist be he wildlife biologist, agronomist, hydrologist, engineer, geologist, planner or economist.

II. General Recommendations for Planning

All of this, then, forms a background for a methodology of planning that includes environmental considerations. Mind you, the problem is not necessarily that an environmental clearance is or is not given. We have been giving clearances of an economic nature on projects since the beginning and our record of cost overruns and economic failure is terribly discomforting. There is no assurance that an environmental check -- simple or otherwise — at the end, middle or beginning of the planning exercise will work much better. This has some fairly important ramifications for the planning exercise which include 1) the mandate of the planning mission; 2) the design of the work by individual disciplines and sectors, and 3) how the planning team is managed and coordinated.

Several recommendations can be enumerated.

1. Environmental quality objective. The mandate of the specific planning exercise must include an environmental quality objective alongside of and generally equal to the economic or social development objectives. The reason for including an environmental quality objective is that environmental quality then becomes an integral

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made to protect public interest and a mechanism should be provided so that public interest is considered when fixing and adjusting objectives, and when the decision on a development project is made.

5. Generation of alternatives. Almost any use of any resource, in any place, at any time will create conflicts between competing interest groups. Use of one resource may mean the destruction of another. Because planning looks toward the development and use of resources, the planning activity is not immune to these conflicts. And clearly their rational resolution is called for before projects are initiated; rational resolution of these conflicts necessitates the generation of alternative plans for development. The number of alternatives, of course, depends upon the number and nature of the stated objectives and their complementarity.

The selection of alternatives as far as possible should not foreclose other developmental options. Methods of identifying a problem of option foreclosure include evaluating the uniqueness of the affected resources and considering the irreversibility of the impacts of a given development project. Although difficult to evaluate quantitatively, these two methods give rise to a preservation value for unique environmental components and processes. This value can be termed the option value or the option demand and is characterized by a willingness on the part of individuals to pay for the option to preserve an area possessing important or potentially important resources and processes that could be irreversibly altered by a development action.

6. Assignment and display of economic and other value to adverse and beneficial impacts. Certainly, a large number of impacts are not quantifiable at all, not to mention quantifiable in economic terms. Others, which are easily assigned to sectors, are included in an economic analysis. For example, commercial forestry and fisheries losses are commonly included as a cost of hydroelectric power project. Additionally, hwoever, attempts have been made to further calculate costs on the basis of a distinction between commodity and amenity resources and the concept can be useful in assigning values to costs and benefits at the early planning levels.

Commodity resources are those that require the intervention of some form of production technology between the resource in its natural state and its use by man; they are those resources that are allocated on the basis of some focus of market mechanism. Examples are the use of forests for lumber, mining of ore for production of metals, and harnessing of a river flow for production of power. Others are given in Table 2.

Amenity resources are used without production technology. Examples are the scenic value of a rare landscape or other values associated with the maintenance free services offered by natural ecosystems (Table 2).

These effects can be expressed as economic values but, if this is not possible, other quantitative and qualitative factors can be used and defined in other terms: their influence on man, the uniqueness of the component (expressed on a simple scale) and the significance of any effect that is irreversible.

In any case this information should be displayed for the decision maker because the consequences of development cannot, without severe distortion, be reduced to a single term such on the benefit/cost ratio. To do so vastly increases the potential for error, and the use of only one term can obscure more information than it reveals. In an attempt to circumvent this danger, both the potentially adverse and beneficial effects of a project should be displayed as completely and as quantitatively as possible. These effects can often be expressed as economic values but, if this is not possible, other quantitative and qualitative factors can be used.

7. Consideration of dynamics and interaction. The world in which we live is one of action and interaction, of cause and effect, of movement and change in both time and space and the planning team must pay attention to the nature and meaning of these interrelationships. To be sure, it is more difficult to measure the properties of dynamic

flag areas of potential significance and to suggest areas requiring further study.

The model represents the flow of energy, materials and information (lines) between components (symbols) within the system and therefore relationships can be visually described. At each interaction there is a loss, change of direction or change of intensity of energy, material or information. Major interactions can be highlighted by a small black dot. These represent major interactions which can be considered as impacts. They are specific points where further study will be required to elucidate the kind and degree of impact.

The model is a visual representation; it can never be complete and is not the final product. It is a tool not unlike a base map. In many ways, it can be considered a base map. It is used to analyze and verify, and, through the interactive process of planning, it can be modified and quantified to the limits of the existing resources and needs.

The symbols which describe the basic elements of the system are:

1) Forcing function -- any input force originating from an energy source outside the predetermined boundaries of the system being analyzed. The symbol used is a circle with one energy flow line coming out (Fig. 4a). At the biosphere scale, the only forcing functions operating on the earth are the sun and the gravitational pull of the moon. These two examples illustrate the great variability in what can constitute a forcing function, yet which have analogous effects from an energy flow perspective. The sun's input is a flow of light energy driving the great air and water circulation patterns by differential heating and providing the basis for photosynthesis by plants. The moon's gravitational pull acts more circuitously, causing the tides to flow in and out of the coastal estuaries twice daily. The tides in turn multiply productivity by irrigation and translocation of food and nutrients. In modern agriculture, sun and rain are supplemented by such man-controlled forcing functions as irrigation, biocides, fertilizers and fossil fuels. While agriculture can exist without any external subsidy save sun, rain and hand labor, man cannot augment crop production per farmer and per acre without some auxiliary fossil fuel inputs. A forcing function may be, or become (if applied at a rate in excess of the optimum), a negative force on a system's productivity. Unseasonal cold or heavy rainfall, excessive pesticide or fertilizer use, or in a resort community, excessive numbers of tourists, are examples of conditionally negative inputs. The basic difference between natural forcing functions such as sun and tide and man-controlled ones is that the former are free while the latter require a fossil fuel energy output to sustain input flow.

2) Component -- a part of a system with a distinct, functional role, depending on the scale and level of detail desired in analysis. A component may be an entire trophic level such as primary producers, herbivores, an industrial sector, or a paper mill. Three basic symbols are used. A bullet shaped symbol (Figure 4b) represents a solar energy dependent photosynthesizing plant species population or cultivated or natural community -- the primary producer trophic level. Only plants are represented by this symbol; there are no manmade analogies. The arrow to ground represents the energy cost of self-maintenance, the pumping out of entropy increase, as required by the second law of thermodynamics. A hexagonal symbol (Figure 4c) is used for any self-maintaining cnsumer component such as the herbivore, carnivore and organic matter reducing and recycling detritivore trophic levels. A power plant, individual or family, or a city are examples from a developed system. A tank-shaped symbol (Figure 4d) is used as a more general term for any energy storage in a system, regardless of trophic level.

All three representations of a component have in common input flows, energy stored as structure (i.e., plant biomass or store inventory), and output flows to other trophic levels and for self-maintenance.

3) Interaction -- workgates or multipliers, shown with an arrowhead-shaped

density and distribution of plant and animal populations, the physical and chemical characteristics of the soil, the distributions of soil and parent rock, and the amounts of precipitation and runoff. The functioning of ecosystems includes such things as nutrient cycling and energy flow; the processes of infiltration, interception, runoff, and evapotranspiration; successional phenomena; phenology; predator/prey relationships; population dynamics and migration; and photosynthesis and respiration.

Environment, as defined in the dictionary, is "something that surrounds." To be useful to us, however, portions of this definition need to be clarified. The question "surrounds what?" needs to be answered and "something" needs to be explained. In the context of economic development, environment is man centered and consists of the stucture and the function of those natural and manmade ecosystems that surround and support human life. Development, then, becomes the manipulation of ecosystems so that human quality of life is improved. This definition of development is somewhat different that the one given above in that it makes concerns for development and concerns for the environment one and the same thing.

Planning is the analysis of resources and demands and the formulation of projects and strategies that utilize those resources to resolve problems and meet needs. All too often planning is narrowly focused in that it looks at the structure of the environment but not at the function. Developmental planners must look at both if ecosystems are to be safely and successfully manipulated.

Both natural and manmade (rural and urban) ecosystems are manipulated in development. Development is not just the manipulation of economics, it is not just the manipulation of the water resource or the forest resource or the soil resource; it is not the manipulation of human populations nor the imposition of modern agricultural technology. It is the manipulation of interactions and relationships between present and future components (structure) and processes (function) of natural and manmade ecosystems.

Ecosystems support human life. That is, the structure and function of these ecosystems support life and it is these that are manipulated. One can make a list of the specific ecosystem components and functions. However, to emphasize their support value in the context of development we can call them "goods and services" without doing too much damage to the economic usage of those terms. Table 2 is such a list.

All ecosystems of course do not contain all of these characteristics. And the value of each changes over space and time. But given the fact of their presence, development is the enhancement, the use, exploitation and/or protection/conservation of these goods and services. The problem is that the use of one often eliminates the uses of others. This then becomes one definition of negative environmental impact. That is, it is the loss or impairment of an ecosystem's goods (structure, form) and services (process, function) due to man's activities in that or allied ecosystems.

For example, Figure 1 represents a forest ecosystem offering serveral goods and services. These are:

1. Tree species having high quality wood
2. Erosion control
3. Scenic recreation
4. Water for downstream navigation
5. Habitat for an endangered species of fauna
6. Habitat for several narrow endemic species of plants
7. Nutrient storage
8. Ornamental plants
9. Sediment control
10. Non-metallic minerals

Given these "resources" a number of development projects could be planned from complete ecosystem destruction to extract the mineral resource, to complete ecosystem

Table 1. Categories identified with the satisfaction of human needs and the human quality of life.

Health	-- Adequate nutrition
	-- Freedom from disease
	-- Freedom from physical trauma
Shelter	-- Protection from the elements
	-- Adequate clothing
Protection from Agression	-- Territory
	-- Personal
Security	-- Work
	-- Personal liberty
Spiritual needs	-- Religion (find his place in the Universe)
	-- Self-confidence (find his place among men)

part of the whole planning process to be treated at each of the planning stages. Further it helps to insure that each member of the planning team has a concern for environmental quality when formulating and evaluating strategies and projects.

2. Explicit treatment of environmental quality throughout the planning process. Explicit treatment of environmental quality is necessary because the planning process increases in rigidity from the statement of the objectives to execution of the program. Therefore, insertion of concerns for environmental quality after initiation of the planning process becomes increasingly more difficult. To place them at the beginning helps assure that they will be considered during the entire process at little extra cost, that later environmental/development disputes will be circumvented and that information for the formulation and evaluation of specific environmental projects will be sought.

In this regard the makeup of the team and the terms of reference for the individual specialists and sectors becomes important. This means the use of interdisciplinary teams. In the past, much of planning was undertaken by engineers, economists and hydrologists for narrowly prescribed purposes. However, the ramifications of development are too broad, and the chance for error too great, for planning to be left to one more or less homogeneous group. Indeed, the problem with the word "intangibles" is that what may be intangible to an engineer or economist may be well understood by a sociologist, anthropologist, epidemiologist, and ecologist. Because the reverse is also true, interdisciplinary planning teams become necessary. Incentives and opportunities for intersectoral and interdisciplinary interaction should be included in the terms of reference for each member of the planning team. That is, discussion and information flow should be mandatory.

3. Coordination of planning efforts with other planning entities. The boundaries of planning units may be defined in many ways: political, social, economic, natural and even arbitrarily. The planning unit may be a state, province, river basin, watershed, airshed, vegetation type, biome, ecosystem, city or neighborhood. What is common to all of these, other than being a unit of space, is that what goes on within the boundaries influences and is influenced by what goes on outside those boundaries. Water runs downhill, winds blow, populations migrate, commerce takes place, traffic moves, money flows and decisions are made (or not made). Because of this, the success of planning efforts depends on the close coordination of planning entities whose work will somehow influence what goes on within the planning area. These may be entities having geographical jurisdictions as well as those that have sectoral jurisdictions. Whatever mechanisms, arrangements or hierarchical structures for coordination are required to consider and resolve issues of non-compatibility of plans, they should be developed.

4. Public participation. In addition to the economic sectors given in Table 4 there is what is called the Public Sector, which can be divided into two subsectors: the "target" population and the "affected" population. Both should be involved in planning decisions. However, the participation of the public in planning is, at the same time, both necessary and problematical. It is necessary because development involves life quality values which vary over time as well as between and within cultures and individuals. Likewise, much of the data on which planning decisions are made are of the most subjective kind. These decisions not only try to predict the future but also, to an even larger degree, attempt to guide the future. Since these can involve the "quality of life" of thousands or even millions of people, it is best that they themselves have the opportunity to say what they want for their future.

It is problematical because, for public participation to be of value, participation must be informed and based on a certain degree of self-understanding. Furthermore, it is problematical because cultures differ in the manner in which political decisions are made, and these vary from the completely democratic to the completely autocratic. Whatever the socio-political-cultural realities, however, efforts should be

Table 2. (continued)

47. Gene pool (fauna)
48. Gene pool (plants)
49. Riverine, lacustrine, marine transportation
50. Metallic minerals
51. Non-metallic minerals
52. Construction materials (sand, clay, cinders, cement, gravel, rocks, marble)
53. Food materials (salt)
54. Mineral nutrient (phosphorus)
55. Space
56. Air-shed (dilution of air contaminants)
57. Population control (pests)
58. Hides, leather, skin
59. Other animal materials (bones, feathers, tusks, teeth, claws)
60. Other vegetative materials (seeds)
61. Energy sources (wind, tides, sun)
62. Fossil fuels (oil, gas, coal)
63. Sport hunting
64. Pet and zoo trade
65. Mineral dyes, glazes
66. Ornamental fish
67. Early warning system
68. Moisture modification
69. Irrigation water
70. Physical support for plants
71. Agricultural production
72. Water for ecosystem maintenance downstream

Table 3. Possible development projects in a forest ecosystem and potential impacts. (-) = negative impact; (+) = positive impact; and (0) = no known significant impact.

Projects	Impacts					
	Present			Future		
	-	0	+	-	0	+
Mining	1-9	-	10	1-10	-	-
Ecologic Reserve	1,10	-	2-9	-	-	1-10
Clearance for Agriculture	1-10	-	-	1-9	-	10
Selective Cutting (Forestry)	2,3,5 6,7,9	10	1,4,8	1-9	10	8

system than it is to measure a stationary state, but it takes only a few well chosen observations on a system to provide useful information. The number and size of the trees in a forest may be important for planning purposes, but a knowledge of the role of the forest in erosion control, water supply, as a food source, the value of its gene pool as well as its replacement potential, successional stages, and position and role in the cycling of nutrients is important for these same planning purposes.

A number of fairly reliable techniques have been developed in systems analysis which can be and are used in planning. Fortunately, they can be used at almost any level of sophistication and can play an important role in organizing a study as well as in analyzing the ecosystems involved. At the early stages of planning, which is where the Program of Regional Development of the OAS works, these involve primarily the use of matrices and conceptual modeling.

III. Planning Methodology

Three things condition the following methodology: 1) an environment characterized by interaction and interrelationships; 2) the resource base is of primary value for the betterment of human life quality; and 3) the planning exercise more often than not is restricted by lack of time, finances and information. To do the job of making efficient, effective, long-term use of the available natural resources through planning, an awareness of interrelationships and interdependency is essential. To make the best use of the available time, finances and information each task throughout the planning exercise must be guided to gain the maximum at minimum cost and time; it requires specific targeting of the terms of reference for the technical team members and, at the same time, a flexible strategy which allows the formulation of viable project alternatives.

This methodology requires:

a. A spatial definition of the major ecosystems or "ecological units" in the region. These may be such things as "life zone" maps but vegetation maps or even general physiographic maps may be used.

b. A list of the ecosystem goods and services for each of the units. Many of these have been given in Table 2.

c. Available information on the "environmental units" including energy sources, food chains, linkages and interactions in order to construct a conceptual model of the region. This model should show the major interactions within the regional system (Figure 2). When a development activity is added to the regional model (Figure 3), specific points of interaction can be located and described according to available information and project objectives. If there is little or no information available, specific points requiring treatment in the planning exercise can be identified. The model will also help identify the processes and structures which offer possibilities for economic development as well as indicating points where impacts would occur.

d. Once the impact points are located, the particular disciplines involved can be identified and terms of reference developed to maintain and orient communication between sectors and disciplines.

e. Once specific projects are identified, an impact matrix or table can be constructed placing project against ecosystem goods and services. The body of the matrix indicates likely changes from a no plan alternative. These then can be evaluated against the criteria of a) quantity; b) quality; c) singularity; d) deterioration; e) reversibility and f) importance.

Conceptual Model

The purpose of the conceptual model is as an aid to the systematic review of relationships within the regional system including those brought on by development activities. It serves to help define the important interactions within the system, to

931. Education
932. Investigation
933. Medicine
934. Welfare
9.4. Recreation
9.5. Personal services
9.6. International organization

0.0 Nonspecific activities

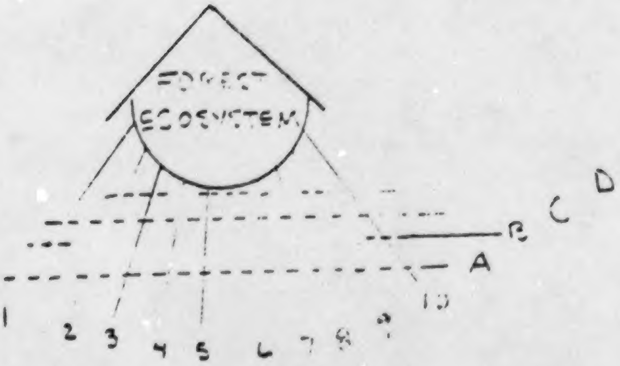


Figure 1. Forest ecosystem offering goods and services and five different potential development projects and their impacts.

symbol, represent the interaction of a major energy flow essential to some process such as crop production. The inputs and outputs are shown in Figure 4e. The control flow entering a multiplier may be a whole number or a fraction. In the latter case, a division or decrease takes place in the energy output flow. A very important consideration in interpreting workgate functions is that the energy multiplier value of a control flow is measured by the magnitude of change in the output flow relative to the input flow over a range of control flow magnitudes, including zero. The cost of creating the control flow is reflected in the maintenance drain. For example, a flood represents an energy flow, the destructive power of which is measured by the crest height. The value of a flood control project (a fractional control multiplier) is measured by the reduction in crest height it produces and the resultant decrease in damage to potentially affected property. The maintenance cost of the project is reflected in the energies expended in creating and maintaining water control structures, floodplain excavation and resettlement, or other action. Secondary and tertiary effects of a project result from additional interactions between the project and other energy flows in the system.

Each symbol in the energy language described above can be expressed mathematically. A process can be modeled, expressed as a series of differential equations, and simulated using an analog computer. Impact assessment involves qualitative conceptual modeling, quantification of significant energy flows and storages for analysis and, if needed, computer simulation.

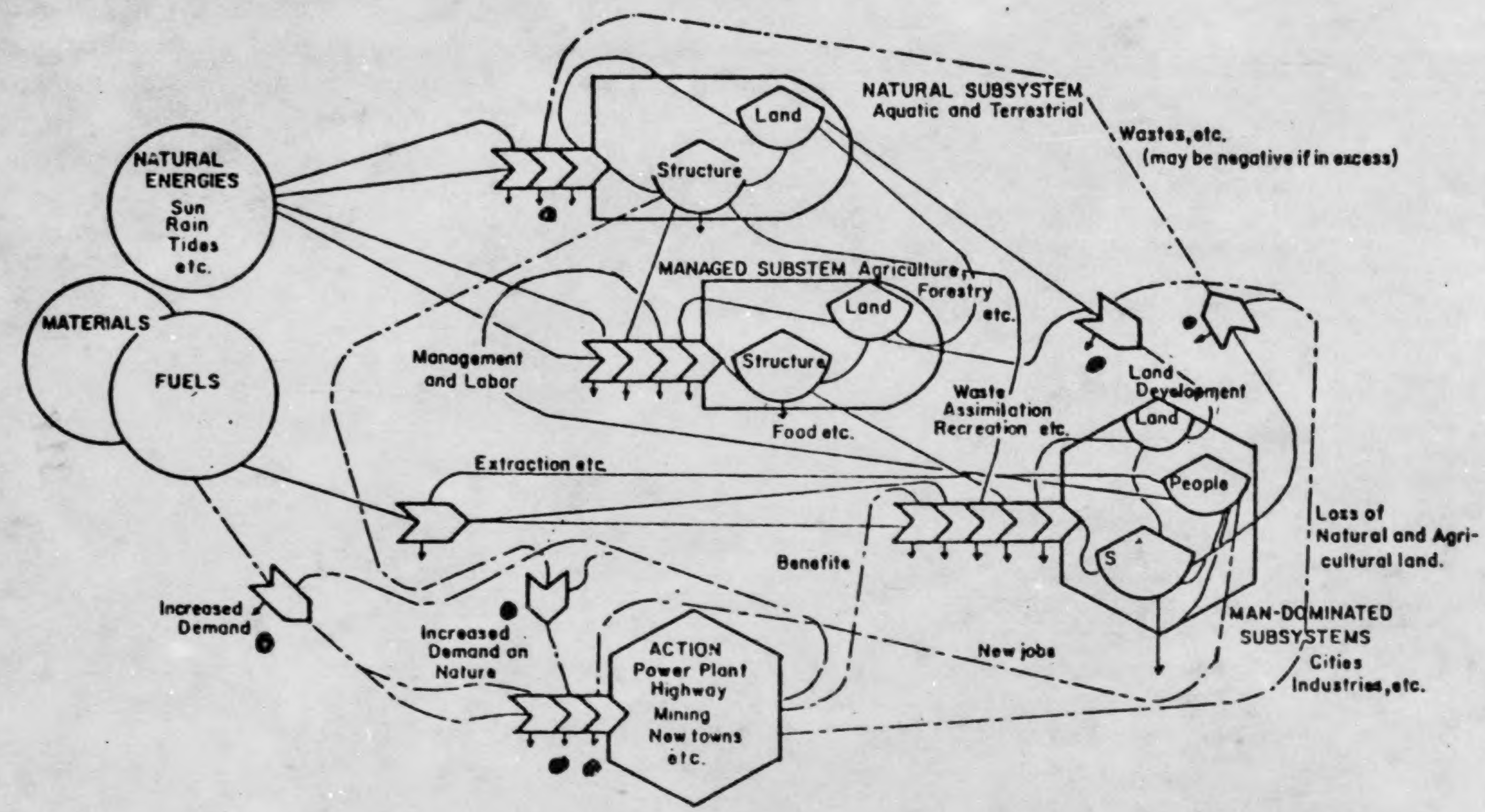

NATURAL SUBSYSTEM
Aquatic and Terrestrial
Land
Structure
Wastes, etc.
(may be negative if in excess)
NATURAL ENERGIES
Sun
Rain
Tides
etc.
MANAGED SUBSTEM Agriculture, Forestry etc.
Land
Structure
MATERIALS
FUELS
Management and Labor
Food etc.
Waste Assimilation Recreation etc.
Land Development
Land
People
S
Extraction etc.
Benefite
Loss of Natural and Agricultural land.
Increased Demand
Increased Demand on Nature
ACTION
Power Plant
Highway
Mining
New towns
etc.
New jobs
MAN-DOMINATED SUBSYSTEMS
Cities
Industries, etc.

Figure 3. The regional ecosystem model of Figure 2 with a typical impact action imposed. Dashed lines indicate processes which must be evaluated.

Table 2. Ecosystem goods and services

1. Nutrient cycling
2. Nutrient storage
3. Nutrient distribution
4. Lumber
5. Firewood
6. Construction materials from wood (posts, vigas, etc.)
7. Vegetation fibers
8. Medicinal plants
9. Food for human consumption (fruits, chicle, honey, sap)
10. Plant chemical substance (dyes, stains, waxes, latex, gums, tannin, syrup, sugar)
11. Food for wildlife
12. Ornamental plants (indoor, outdoor, dry)
13. Habitat for wildlife
14. Windbreaks
15. Shade
16. Potable water
17. Hydroelectric power
18. Industrial water
19. Recreational use of water
20. Dilution of contaminants
21. Decomposition of contaminants
22. Erosion control
23. Sediment control
24. Flood control
25. Habitat for aquatic life
26. Food for aquatic life
27. Food fish (crustaceans, fin-fish, mollusks)
28. Food for livestock (fish meal)
29. Fertilizer (fish meal)
30. Fertilizer (guano, other dung)
31. Fuel (dung, peat, charcoal)
32. Aquatic plants for food (algae)
33. Aquatic precious-semiprecious materials (pearl, coral, conchas, mother of pearl)
34. Sport fishing
35. Ecosystem regulation (faunal)
36. Ecosystem regulation (vegetative)
37. Forage for livestock
38. Scenic tourism
39. Recreation tourism
40. Scientific tourism
41. Scientific values
42. Spiritual values
43. Historical values
44. Cultural values
45. Endangered species (fauna)
46. Endangered species (plants)

Development Applications of Water Resources
Upstream/Watershed Management
U.S. A.I.D. in ASIA

by

John E. Roberts
Agency for International Development
Office for Project Development, Asia Bureau
1979

Introduction

The Agency for International Devlopment, under a variety of pseudonyms, has provided U.S. economic foreign assistance since the late 1940's. Today, AID provides economic assistance to 75 developing nations of the world. U.S. bilateral assistance is provided under annual appropriation authority of the United States Congress and is provided relative to country needs, country commitments, absorbtive capacity, and U.S. interests. This assistance is appropriated in the following functional categories: Agriculture/Rural Development, Health, Population, Education/Human Resource Development, Science/Technology/Energy, Special Development Problems, and Food for Peace.

Over the past few years, the United States Congress has provided an average of $750 million annually to A.I.D. for projects related to Agriculture/Rural Development; roughly 2/3 of the annual totals. For the nine country programs administered by the Asia Bureau, annual appropriations have recently averaged $500 million, of which, about $325 million are designated for Agriculture/Rural Development activities. These nine countries (Bangladesh, Burma, India, Indonesia, Nepal, Pakistan, Philippines, Sri Lanka, and Thailand) have a total population well in excess of one billion people. Since 1978 almost every Asian A.I.D.-recipient nation has been implementing water management and/or upper watershed projects with U.S. financing. This, of course, reflects the critical needs now fully recognized for better conservation and applications of water resources, worldwide. As we move into the new decade of the 1980's, and the United Nations declared "Water Decade," the emphasis on water resources will expand even further.

More than $171 million of A.I.D. assistance to the above nine countries is presently being utilized to implement a variety of water and watershed management-related projects. The objectives, intended impacts, and specific foci of these projects, naturally, differ from one country to another. Some examples are as follows:

Bangladesh:	Integrated Land & Water Use Water Management/Rural Irrigation
Indonesia:	Provincial Area Development Program (Several components are directly applicable) Sederhana Irrigation & Land Development † Citanduy Basin Development (including $17 million A.I.D. and Government of Indonesia contributions for 12,000 ha of upper watershed restoration, development and water control)
Nepal:	† Resource Conservation & Utilization (focused on 6 specific and representative watershed areas)
Pakistan:	† Barani-Rainfed Land & Water Management Water Management Research

Table 4. Economic sectors. (Adapted from Uniform International Industrial Classifications of All Economic Activities: Statistical Report N. 42, 1969. Department of Economic and Social Affairs -- U.N.)

1. Agriculture, hunting, silviculture and fisheries
   1.1. Agriculture and hunting
   1.2. Silviculture and timber harvesting
   1.3. Fisheries

2. Mining
   2.1. Coal
   2.2. Petroleum and natural gas
   2.3. Metallic minerals
   2.4. Other minerals

3. Industry
   3.1. Food, drink and tobacco
   3.2. Textiles, leather goods, furs
   3.3. Wood products
   3.4. Paper
   3.5. Chemical
   3.6. Non-metallic minerals
   3.7. Metallic minerals
   3.8. Metallic products

4. Energy
   4.1. Gas and steam electric energy
   4.2. Hydroelectric energy

5. Construction

6. Commerce
   6.1. Wholesale
   6.2. Retail
   6.3. Hotel and restaurants

7. Transportation, storage, communication
   7.1. Land
   7.2. Water
   7.3. Air
   7.4. Communications

8. Financial
   8.1. Financial establishments
   8.2. Insurance
   8.3. Real estate

9. Services
   9.1. Public administration
   9.2. Sanitation
   9.3. Social services

(a) Decreasing soil erosion by 80% to no more than 5 tons per acre annually,

(b) Reducing run-off by 50-80% during the monsoon season (Kharif) and 10-40% in the winter season (Rabi),

(c) Significant reductions in sedimentation, and

(d) Generally increasing the areas and magnitudes of agricultural production.

Planned project objectives or outputs include:

(a) An effective system of agency/departmental coordination,

(b) Specialized training of soil and water management teams,

(c) Organization of and assistance to farmers, and

(d) Putting into practice vegetative cover erosion control measures.

Nepal

Upper watershed problems in mountainous Nepal are even more difficult. The problem here affects a majority of the country where more than 10,000 square kilometers are totally devoid of vegetation and are entering a period of actual desertification. It has been estimated that more than 240,000,000 cubic meters of soil are annually being carried out of Nepal (to India) by the nation's four major rivers, fed by some 6,000 tributaries. These figures translate into an annual loss of 50 to 75 tons of soil per hectare of potentially productive land. (A comparable U.S. figure is 2.5 to 12.5 tons of soil per hectare.) Much of Nepal's forest resources have been destroyed for timber, fuelwood, and grazing. As a result, valuable nutrients have been leached out of what soil is left and serious landslides are becoming the rule rather than the exception.

USAID and the Government of Nepal are beginning a $6 million project entitled Resource Conservation and Utilization (RCU) to attempt rectification of these major problems in six experimental pilot areas of the Terrai, middlehills, and mountain regions. The Nepalese national counterpart is semi-autonomous Agricultural Projects Services Center (APROSC), but includes design and implementation committees from various geographic/administrative/development zones and Panchayats (districts). The U.S. counterparts under the U.S. Foreign Assistance Act, Title XII, are the universities and institutions linked to SECID (Southeast Consortium for International Development).

The RCU project includes detailed design/application efforts, training of policy-level and management personnel, national-regional-local workshops and seminars, and ongoing demonstration activities in the six pilot areas to introduce seedlings, forage crops, and to undertake small construction schemes such as drains, ditches, check-dams, and water diversions.

As a complement, a recent joint study by the FAO, ODA (U.K.) and A.I.D. recommended the establishment in Nepal of three-year B.Sc. courses in watershed management/forestry at Khairenitarh, one-year certificate courses, on-the-job local training courses, and a concentrated national Institute of Renewable Resources.

If the objectives and targets of the Resource Conservation and Utilization project are to be met, the results must be seen both promptly and in the long-term. This new project hopes to

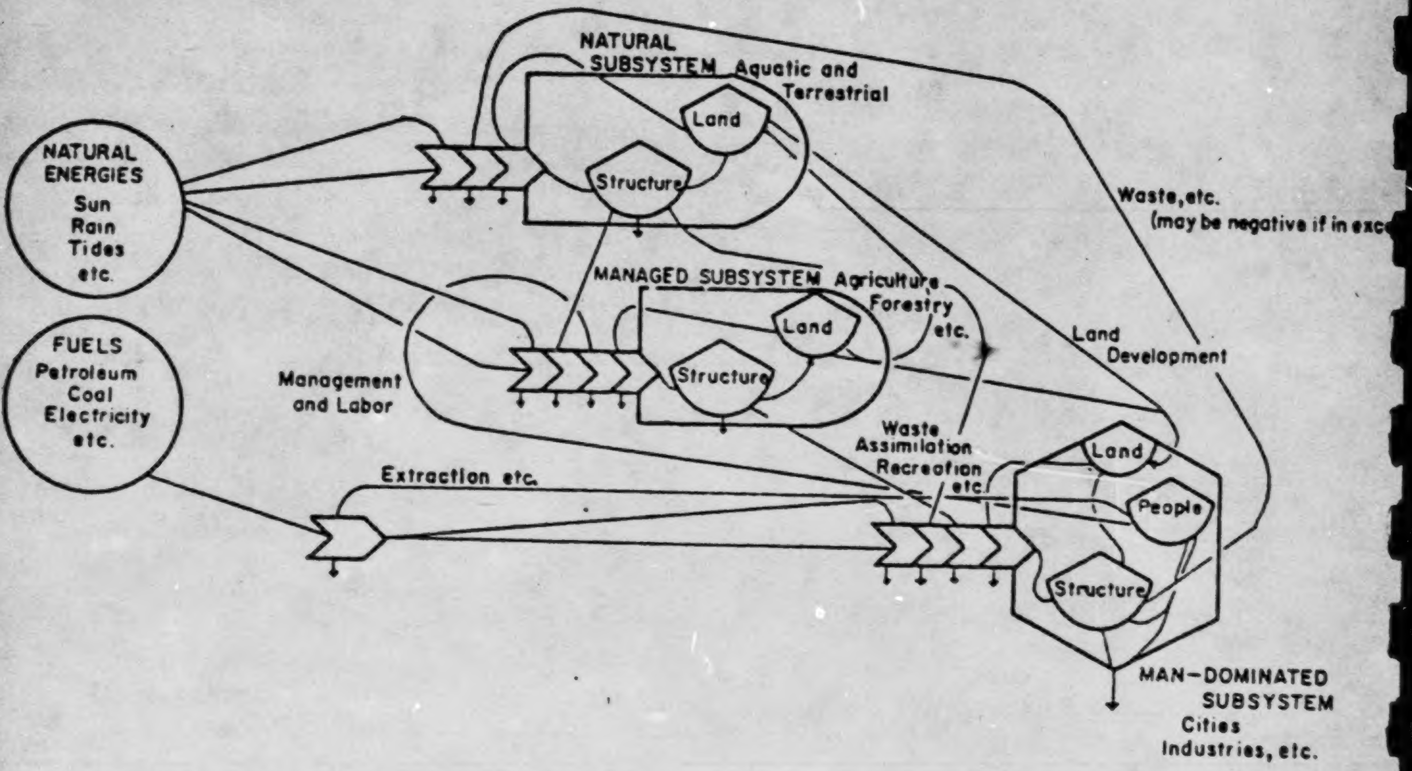

NATURAL SUBSYSTEM Aquatic and Terrestrial
Land
Structure
NATURAL ENERGIES
Sun
Rain
Tides
etc.
FUELS
Petroleum
Coal
Electricity
etc.
Waste, etc.
(may be negative if in exc
MANAGED SUBSYSTEM Agriculture
Forestry
etc.
Land
Structure
Management and Labor
Land Development
Waste Assimilation Recreation etc.
Extraction etc.
Land
People
Structure
MAN-DOMINATED SUBSYSTEM
Cities
Industries, etc.

Figure 2. Generalized model of a regional ecosystem illustrating the interactions among the natural, managed, and developed subsystems. Dependence of man's subsystem upon free natural services is shown.

(d) Increase village communal woodlots, hedgerows, etc., by 400,000 acres, and

(e) Establish three or four national nurseries providing annual forest seedling production of 3 to 3.5 million.

The Sri Lankans are fully aware of the value and need for their forest reserves, particularly in the upper basins. They are convinced that forests and appropriate vegetative cover are the solution to their massive planned development and resettlement programs for some 1.2 million people in the lower basin areas which are so dependent upon the status of soil erosion and water flow control.

Indonesia

The case study of Indonesia, at least focused on the core island of Java with 87 million people, represents one of the most critical and important examples of the need for effective development application of water resources. Population pressures have resulted in intensive and extensive methods of agriculture (primarily rice cultivation) being applied on every type of available land, both lowland and highland. It has been estimated that more than 1/3 of the families on rural Java are landless and, for those having any access to production assets, the average farm unit is less than .3 ha.

In 1975, the Government of Indonesia in cooperation with USAID began a major development project of flood control and irrigation rehabilitation/extension in the lower basin of the Citanduy River. The area of this basin, which is subject to increasingly severe annual flooding and inundation, is over 100,000 hectares, under the administration of 4 Kabupaten (districts) within 2 provinces (West and Central Java), and contains over 2.8 million people, of which 1.2 million are directly engaged in agricultural production. The Citanduy River Basin Development Project is administered as a central government project by the Directorate of Water Resources, Ministry of Public Works with initial investment of $19.5 million from USAID and the Government of Indonesia. Primary objectives of the project were to provide for new and rehabilitated irrigation for more than 13,000 hectares of paddy land, construct and rehabilitate 200 kilometers of flood levees, thereby providing flood protection for more than 60,000 hectares of paddy land. The project also provided for long- and short-term training in watershed management, O & M, and flood control.

A few months ago, the project was assessed and formally evaluated. A.I.D. evaluation regulations, as mandated by the U.S. Congress in Section 102(d) of the Foreign Assistance Act, was intensively applied to the project and its goals and objectives. For illustrative purposes, portions of the non-quantitative evaluation results for the Citanduy project (which are applicable to all A.I.D.-assisted development activities) are shown below:

I. General Project Impacts:

A. Demonstrate Increases of Agricultural Productivity:

-Flood damage protection.
-Water provided by irrigation.
-Farmer risks reduced, agricultural inputs encouraged, yields consequently raised.
-Concurrently, improved practices in the upper watershed increased production.

B. Reduction of Infant Mortality:
-Prevention/reduction of flooding has reduced water-borne diseases.

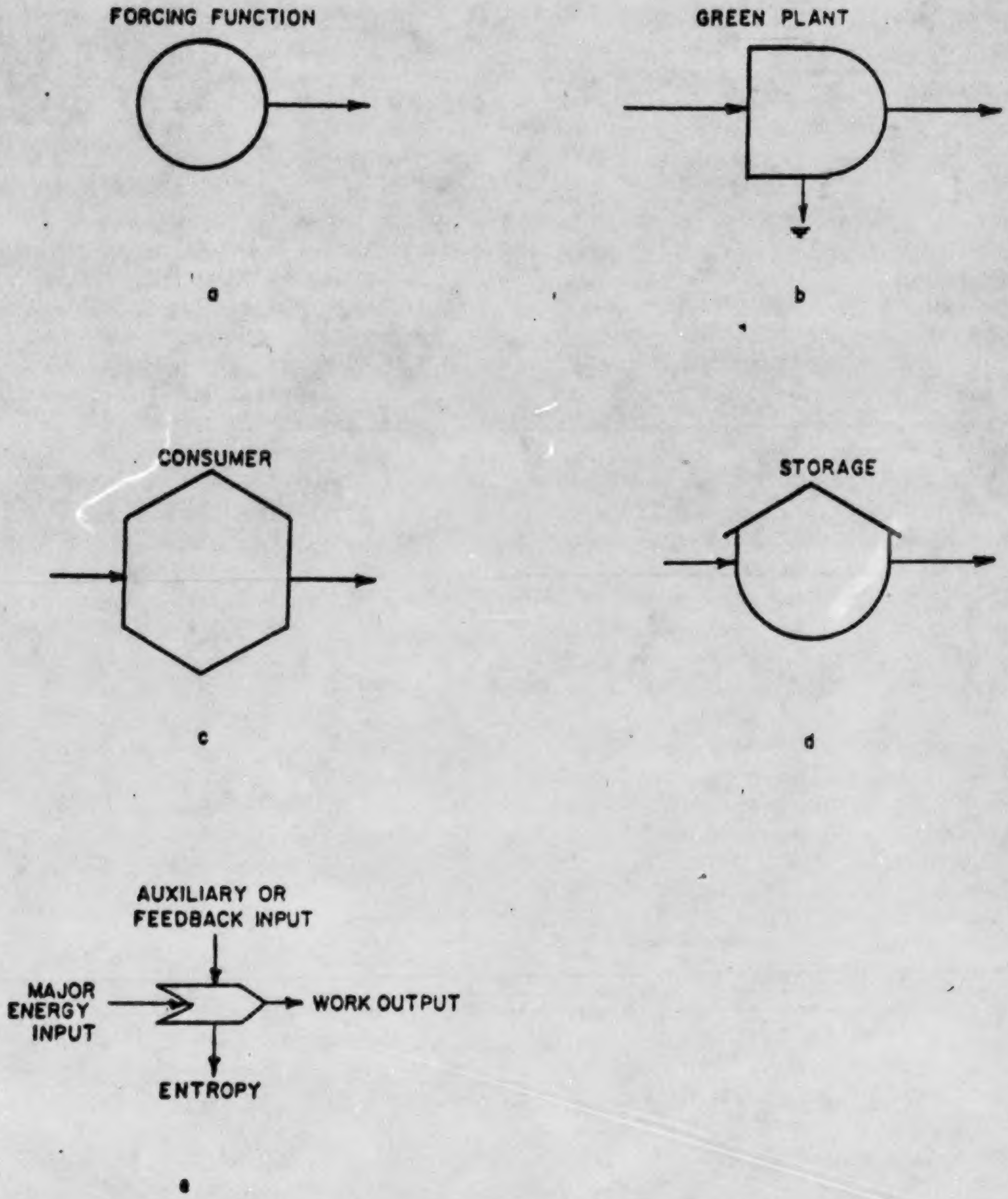

FORCING FUNCTION
a
GREEN PLANT
b
CONSUMER
c
STORAGE
d
AUXILIARY OR FEEDBACK INPUT
MAJOR ENERGY INPUT
WORK OUTPUT
ENTROPY
e

Figure 4. Basic energy flow modeling symbols.

(Flood control contributes to all objectives, which protects crops, which encourages greater investment, which increases yields.)

V. Important Extra-Consequences of Project:

- -Increased the well-being of even poorer upland mixed-crop farmers.
- -Upper watershed sub-project evolved in Panawangan which is increasing upland food production and employment.
- -Assistance is being provided in back-sloped terracing and vegetative practices. Agricultural production and labor opportunities are increasing. Both upper and lower basins are receiving protection.
- -Project has encountered a widespread phenomenon of developing a "project constituency" and is rapidly creating a "climate of opinion" in both West and Central Java.
- -Regional and local public officials (Planning Boards, Public Works, Agriculture, Universities, Technical Schools, etc.) are all taking active and operational interest in project, far and above their roles as envisaged by the Directorate of Water Resources.
- -Local leaders and spokespersons have added to the innovation and continuity of the project's integrity. This condition is developing without direction of any central comprehensive authority, and it appears to be self-sustaining and growing.
- -Auxiliary agricultural inputs agencies, formerly ignoring the project, have voluntarily returned. The Department of Forestries is assuming a major role in the upper watershed. The momentum is growing from the voluntary and evolving coordination of existing institutions.

VI. General Problems

- -Problems continue with local currency budget cycles and construction-year opportunities.
- -Topographic mapping and design/feasibility studies are inadequate or unavailable. There are no aerial photographic maps.
- -Project expenditures are slow. Deadlines are being missed.

In reviewing the various aspects of this evaluation and being generally familiar with the project area, both in the upper watershed area and the lower basin, it is impossible not to be impressed by the "unplanned successes" in the upper watershed. In fact, the most surprising aspect of the initial project itself is absence of any formal attention to the upper watershed and the singular focus on the 100,000, or so, hectares of the lower river basin. The source of the water resources for the primary project area, and, not so surprisingly, the cause of the increasing flooding problems, emanates in the upper watershed.

The upper watershed and the successful complementary pilot project area of Panawangan is no longer being ignored. The enthusiasm of the people in Panawangan for the add-on pilot project is matched by the enthusiasm of the local and regional government officials and by both neighboring and far-flung upland farmers from all over Java. It has become a show-piece for local leadership, farmer participation and inter-agency coordination. Other upper watershed management projects are now beginning to use the model and momentum of Panawangan as their guide. The farmers of Panawangan are even providing "exportable technical assistance" to nearby upland areas. The Javanese have cultivated rice on terraces for generations, but the steeper the slope, the greater the chance for problems. Although they built "bunds" or lips on the terraces, they do not withstand heavy, prolonged rain. Now terraces are being sloped backward into the hillside, and excess water is carried away by rear ditches, then carried downward through bamboo or rock-lined trenches with descending trenches intersecting with other laterals to allow controlled drainage of excess water.

Philippines:	Agro-Forestation
Sri Lanka:	† Reforestation and Watershed Management Water Management Mahaweli Basin Development (Design and Supervision)
Thailand:	Highland Integrated Rural Development (Mae Chaem Watershed)

† Various aspects of these four projects are discussed in greater detail and relationship to the development applications of water resources in other sections of this paper.

Development Applications of Water Resources in Asia

Pakistan

The Barani highlands are found in the Punjab Province, Rawalpindi District of Pakistan. More than 14 million people live in this geographic watershed, known in Pakistan as the regional exporter of the nation's water and power. Much of this water export has undesirable effects, both for the Barani (which loses more than 3,000,000 acre feet of water annually through run-off, thus causing high degrees of nitrogen depletion in the soils) and for the downstream basin areas of Pakistan which are presently incapable of using or controlling so much excess water. Due to these water losses, the region is also unwillingly exporting from 8 to 27 tons of soil annually from each acre! (The disastrous results of this soil erosion are not recognized by the people of the Barani, but are well known throughout South Asia for their cause/effect on the Tarbela Dam Project.)

As long ago as 1968-69, the United States Department of Agriculture (USDA) and A.I.D. conducted a study entitled "Resource Management for Rainfed Regions of West Pakistan." The recommendations made within the study called for:

(a) Improved provincial administration,

(b) Long range national policies,

(c) Recognition of various socio-economic problems within the region,

(d) Development of localized strategies,

(e) Encouragement of local participation,

(f) Increase of effective water resource personnel through training opportunities,

(g) Expanded research, and

(h) Development of pilot demonstration projects.

These types of approaches are not extraordinary given the degrees of the problem and they were, no doubt, needed. They are even more needed today.

An action project entitled 'Rainfed Land and Water Management estimated to cost up to $52 million has been proposed for implementation in many of the sub-project areas of the Barani. The project is proposed for various pilot activities in sites ranging from 30 to 3,000 acres. It relates directly to Pakistan's Fifth Development Plan (1977-83) and calls for integration and coordination within the disciplines of soil and water conservation, forestry, range management, watershed management, and agricultural extension. Project targets call for:

B. Village Cooperation/Coordination
The efforts to save the upper basins and make them productive requires joint and communal efforts, sacrifices, and benefits. Such activities are incorporated in the terraces, spillways, catchments, reforestation, etc.

C. Multi-crop Focus
Single crop production is most difficult in saving and revitalizing the upper watersheds. Most successes have occurred with the Integration of agricultural production beyond paddy with livestock, fish, fruit, legumes, grains, tree crops, etc.

D. Local Leaders
Local projects because they are small in implementation and benefits are focused almost totally on the involved local area. Local leaders must be allowed to have primary and major roles in the project, and have end-result responsibility. Centralized bureaucracies and visiting officials from the capital cannot be ultimately responsible.

E. Delayed Synergistic Benefits
Benefits from such projects cannot be seen immediately nor can they be separated or isolated. These joint benefits accruing from project activities include run-off rates/siltation and flood controls which are not controllable or measurable until full vegetative cover is restored and control infrastructures are operational. Improved filtration and improved water tables may not be quantifiable for several years.

Upper watershed development projects must be self-sustaining and self-beneficial. While they are necessary to protect the lower basins, they must be successful entities in and of themselves, since there is no easy way for measuring compensation to highlanders from lowlanders for improving the upper watershed. The highlanders must be able to compensate themselves.

In contemplating the "lessons learned," it should be stated that informal project managership, both by host country and foreign technician counterparts, have proven most successful. While planning and implementing a project must be formal and as precise as possible, the informality refers to the outside approaches of project managers. These approaches are in making and maintaining connections among and between the official participants and the people. Personal linkages and direct access should be applied to various horizontal levels within the project community, and, if possible, up and down the vertical lines of government organization. Such liaison approaches will serve to remind all concerned of the overall project concept, maintain a concentration on the goals, targets and objectives of the project, and tend to prevent bureaucratic or technical fragmentation of the participants.

NOTE: This paper only represents the research and compilation of ideas by the writer. It does not represent in any way an official position or attitude of the Agency for International Development or the United States Government.

concentrate on the replanting of Nepal's steep slopes with fast-maturing, dual purpose fodder and fuelwood.

It plans to improve livestock management on the less steeply sloped pastureland, and it intends to introduce new varieties of agricultural production on the upland terraces above 9,000 feet in altitude. The very future of Nepal may depend upon its success.

Sri Lanka

The situation in Sri Lanka, the island nation off the southeast tip of the Indian subcontinent, while not as immediately critical as that found in Nepal, is nevertheless as important. One of the most encouraging aspects of the overall water resource issue is the priority attention it is now receiving throughout the world and in every nation. This issue is also not being viewed in isolation, but is being addressed in terms of its impact on and relationship to the environment and to development.

Like much of the world, upper watersheds in Sri Lanka have been rapidly and drastically depleted. As late as 1960, 44% of the entire island was forested. Today, only 21% (3 million acres) has forest cover. Another 260,000 acres are in forest plantations. There is presently an immediate and critical need to reforest 100,000 acres in Sri Lanka's upper watershed basins. The Government of Sri Lanka has recognized this need. Their national development plans provide a high priority for the maintenance of adequate and suitable forest reserves on behalf of the national environment, the applied practice of soil and water resource conservation, and the preservation of the national eco-systems.

Sri Lanka's Forestry Department contains more than 450 full-time employees. Using their own resources, they have raised their capability for the general reforesting of reclaimed lands from 200 acres per year in 1940 to nearly 20,000 acres annually today. At the same time, as pointed out earlier, forest resources are dwindling and the misuse of watersheds is growing.

With USAID, the government has proposed a $7 million project entitled Reforestation and Watershed Management. This project proposes to begin by replanting 15,000 acres in the Upper Mahaweli Catchment Basins (the minimum start required to ensure adequate resources for downstream, and resettlement programs) and 70,000 acres of new fuelwood plantations. Targets of this project include:

(a) Establishment of a national upper watershed policy,

(b) Strengthening the capabilities of the Forestry Department,

(c) Conducting a land use/suitability study incorporating aerial surveys,

(d) Development of a forest/watershed extension service, and

(e) The conducting of an effective public publicity campaign.

This project, as viewed by Sri Lanka, is seen as the first component of a long-range policy and plan. The broad-scope targets are to:

(a) Reforest 100,000 acres of the 1.34 million acres in the upper watershed of the Mahaweli (which since 1956 has seen 114,000 acres denuded),

(b) Reforest at least 400,000 acres of Sri Lanka for commerical timbering,

(c) Establish fuelwood plantations covering 250,000 acres,

Evapotranspiration Notes

compiled by
Lloyd Gay

Outline

Introduction

Evaporation Principles

Evaporation from Lakes
- Calculations: mass transfer approach
- Calculations: evaporation pan approach

Potential Evapotranspiration
- Pan evaporation models
- Empirical models
  - A Temperature Model
  - A Radiation and Temperature Model
  - A Net Radiation Model
  - The Combination Model
- Comparison of models
- PET examples

Actual Evapotranspiration
- Adjustments to PET
- The Water balance
- The energy balance

Literature cited

Introduction

These notes on evapotranspiration are an informal compilation from a variety of sources. Their purpose is to assist shortcourse students in covering certain aspects of this important topic in the hydrologic cycle. These notes have been greatly influenced by the following:

Doorenbos, J., and W. O. Pruitt, 1975 Crop Water Requirements. Irrigation and Drainage Paper 24. FAO, Rome. 179p.

Dunne, T., and L. B. Leopold. 1978. Water in Environmental Planning. W. H. Freeman and Company. San Francisco. 818p.

Gay, L. U. 19__. Potential Evapotranspiration in Deserts. (in press).

Hounam, C. E. 1973. Comparison Between Pan and Lake Evaporation. Tech. Note 1216, WMD, Geneva. 52p.

C. Population Growth Controlled:
-Not applicable.

D. Broadened & Equitable Income Distribution Promoted:
-Poorer populations in flood-prone areas were benefited.
-Irrigation availabilities enhanced and better water distribution provided to end-of-the system poorest farmers.

E. Under & Unemployment Reduced:
-Protection against flooding has produced higher yields, thus more work.
-Anti-flood and irrigation infrastructure construction has been labor intensive.

F. Related Project Imparts
1. Creation or strengthening of institutions which assist socio/economic development:
-Training has promoted better water resource utilization and better coordination/application of agricultural development agencies.
2. Improvement in Social/Political/Economic Conditions of Women:
-Primary agricultural roles for women have expanded through the agricultural extension program.

II. Profile of Beneficiaries

A. Direct
1. Income: Farmers in area (appx. 1.2 million).
2. Labor Provision: Construction laborers (5,000).
3. Agricultural Production: 900,000 people from improved irrigation and agricultural practices.
4. Education/Training/Management: Government officials, engineers, and farmers.
5. Medical Treatment: Not applicable.
6. General Living Conditions Improved: Water, housing, sanitation, nutrition.

B. Indirect
1. Area Population:
Food Increases - Yes
Increased Mobility - N/A
General Health Improvement - Yes
Overall Economic Improvement - Yes
Number: Approximately 2.8 million
2. People NOT affected and why: —
3. People adversely affected and why: —

III. Project/Sector Goal
-Decrease dependency on food imports.
-Improve well-being of area's poor majority.

IV. Project Purpose
-Reduce flood damage.
-Increase rice and other food-crop production.
-Further integrated basin development.
-Irrigation systems and upper watershed management.

Water molecules moving out of the liquid produce a vapor pressure, which is a function of the rate at which water molecules leave the surface, and therefore of the temperature (energy) of the surface. Some molecules of water vapor move from the atmosphere into the liquid and condense. The rate at which they do so is directly proportional to the vapor pressure of water in the atmosphere, which in turn is controlled by its water vapor content. Evaporation is the net rate of movement out of the liquid and is therefore directly proportional to the difference in vapor pressure between the water surface and the atmosphere. This difference is called the vapor pressure deficit.

If the air above an evaporating surface were still, the addition of water vapor to the lower layer of air would soon raise the atmospheric vapor pressure to that of the evaporating body and the air would be saturated with water vapor. If this condition is to be avoided and evaporation is to continue, the surface layer must be removed and continually replaced by unsaturated air. The major mechanism for replacing the surface layer of air is wind, which creates the turbulence responsible for moving saturated air away from the evaporating surface.

Four conditions are necessary, therefore, for continued evaporation: a source of water, energy, a difference in vapor pressure between the water and the atmosphere, and a method of exchanging surface air for air capable of holding more water vapor.

The energy requirement for vaporizing water is precisely defined (L = 585 cal/g at T = 21.8°C). There is a slight dependence upon temperature, but 535 cal/g is an adequate working value for latent energy of water. There is full equivalence between energy and mass of water vapor, so evaporation can be referred to in terms of energy or of depth equivalent.

Recall that 1 cm depth of water is really a volume per unit area ($1\ cm = 1\ cm^3/1\ cm^2$). Thus 1 cm depth of water evaporated is the same as $1\ g/cm^2$, which utilizes $585\ cal/cm^2$ in the vaporization process. The exchange could be viewed as either $585\ cal/cm^2$ of latent energy or as 1 cm depth of water; the two sets of units are equivalent. Using the symbols L for latent heat of fusion ($L = 585\ cal/g = 585\ cal/cm^3$), $E(g/cm^2)$ for evaporation, and LE for latent energy, we see that $E = LE/L$ and $LE = E \times L$. The convertability between energy and mass of evaporated water will prove exceedingly useful in evaluating evaporation later in this discussion.

It will also be possible to evaluate evaporation through the "mass balance" approach, based upon the Principle of Conservation of Mass. For our purpose, we shall state that the change in mass (or volume) of water during a specified time in a specified volume will be equal to the gains in water minus any losses of water. This can be a very powerful tool.

Consider the simple case of a pond with no surface inflow or outflow, and no seepage. The only gain is by precipitation (P) and the only loss is by evaporation (E). Then the mass balance is simply

$$\text{Change in Volume} = P - E.$$

The evaporation can be measured very simply by measuring P and observing any changes in depth in order to estimate changes in volume.

The mass balance technique can be applied to ponds, lakes, glaciers, the soil volumes and entire watersheds. The concept can also be used with the energy equivalent of evaporation in an "energy balance" evaluation. Both methods will prove useful in estimating evaporation.

The availability of water plays a major role in the rapidity of the evaporation taking place. While a supply of liquid water (cloud droplets, lakes, etc.) is necessary in order for evaporation to proceed, the supply need not be on the surface if it is available within the rooting zone of vegetation. The evaporating surface is within the stomata of the leaves when vegetation is

Economic development for the villages and businesses in the upper watershed is growing rapidly and agricultural activities are diversifying and expanding into livestock, forage planting, fish breeding, multi-cropping, etc.

General Approaches and Lessons Learned for Development Applications

It may be strenuously argued that successful development applications for upper watershed areas, like those for any area or sector, cannot be generalized. What might work in one nation (or region, or province, or village) will not automatically or systematically work in every other or in any other. Physical and visual progress in the construction, rehabilitation, or revitalization of requisite infrastructure or public works, despite unplanned delays or problems, are always the easiest aspect of a project to plan and implement. Nevertheless, the more critical and difficult project components necessary for success involve roles of farmers and local leaders, the integration of technologies employed, the administrative/budgetary methodologies, the coordination apparatus established and applied, etc. It is also always best to begin small, with manageable pilot areas or demonstrations. Limiting the size and scope of projects allows for in-depth attention to the necessary elements of site coordination, intensive training, etc. Successful water management projects, particularly in upper watersheds, require long beginnings and nurturing. This period should usually occur over a one to two year period, then be followed by another two year consolidation period. If after this three year period of start/consolidation the project(s) have established good and relatively successful foundations, expansion and replication with the necessary modifications to meet the new or changed situations have high probabilities for success. Premature expansion before a reasonable period of time which is necessary to evaluate and assess the pilot demonstration endangers the entire activity. The history of "development processes" is replete with failures which have been caused by impatience. This is all very difficult because no one can argue that the critical need or crisis situation requiring attention does not exist, particularly in most upper watersheds. The tendency is to expand and push those activities which "appear" successful. Most bureaucrats, technocrats, planners, and common people are all alike in exhibiting their impatience and their interest to "do something." Certainly "something" must be done, but the problem is so severe, that the doing something must be correct; it must work; and it must be sustained and long-term. Nothing will serve to embitter farmers or local leaders as much as an abandoned or unsuccessful project. Nothing is so certain to have a disastrous impact on the already precarious ecological system (and the mental outlook of the project advocates) as an unnecessary project failure. This does not mean that starting "small" automatically will be successful or that it rules out speedy or massive programs. On the contrary, while the small starts must succeed in the initial and consolidation phases, the geometric growth of replication can be widespread and sustaining thereafter.

If nothing else, the past experiences and a pocketful of "failures" in upper watershed applications of development have provided some valuable lessons. The following appraisal "checklist" was suggested by the former (for 3 years) USAID counterpart Project Manager (from 1975-78) of the Indonesia Citanduy Project. Under his influence, the pilot upper watershed sub-project at Panawangan evolved and was made an unseparable, integral part of the lower basin development program.

Successful Upper Watershed Management Projects require the following:

A. Grassroots Participation
Since over 90% of the project is by and for the local people, often unlike major downstream irrigation infrastructure, this local participation must control the identification, planning design, implementation and evaluation of the project.

slightly, even after a lengthy passage across a large lake. There will thus be little difference in the evaporation rates from large and small water surfaces under conditions of high atmospheric humidity. If, on the other hand, the initial humidity of the air is very low, it may be considerably increased while crosssing a large lake, so that the proportional decrease in the rate of evaporation as compared to that from a small water surface will be much more significant.

Calculations: mass transfer approach

The effects shown in Figure 2 are those of humidity and area (windspeed is held constant in the Figure). These effects are analytically expressed in Dalton's Law, commonly known as the mass-transfer method.

The mass-transfer method of calculating evaporation is based on the assumption that evaporation is controlled by the windspeed and vapor-pressure difference between the water surface and the atmosphere as follows (Dunne and Leopold, 1978)

$$E_L = N\, f(u)(e_s - e_a) \qquad (1)$$

where E_L = lake evaporation
N = a constant, known as the mass-transfer coefficient
$f(u)$ = a function of windspeed
e_s = vapor pressure of water surface
e_a = vapor pressure of the air.

To apply the mass-transfer technique, a measure of the water surface temperature is required to derive e_s. If plans for a reservoir are being considered, it will not be possible to measure the water temperature because the lake does not yet exist. In such cases, air temperature is often used as a surrogate for the water surface temperature, or pan evaporation data must be used. The atmospheric properties of windspeed and vapor pressure must be measured at a specified height. The formulation used here is for u and e_a at 2 meters above the lake surface.

Values of N for reservoirs in the arid southwestern United States vary with lake area (A) according to the relation (Dunne and Leopold, 1978)

$$N = 0.000169\, A^{-0.05} \qquad (2)$$

where the mass transfer coefficient is calculated for evaporation rates in cm/day, windspeeds in km/day, vapor pressures in mb, and lake area in sq km. Because of the variaton of units in the literature, care should be taken when comparing the mass-transfer coefficients obtained by different authors. Figure 4 (from Dunne and Leopold, 1978) portrays the data available at this time. There is considerable scatter about the relationship described in Equation 2; errors of up to 25 percent are possible if N is estimated from this curve, even in the area for which it was developed. If the evaporation estimate needs to be fairly precise, therefore, a local field study is advisable.

Calculations: evaporation pan approach

The evaporimetric method is the simplest and the cheapest of the known methods of estimation of lake evaporation. The evaporation mesured by a pan or tank evaporimeter is also the most direct index of the evaporation from a water surface. Instruments of this type were apparently first used almost 300 years ago by Halley, but their general use as meteorological network instruments is comparatively recent. One virtue of pan data is that a considerable amount has been collected and that such data can be used both before and after the construction of water reservoirs.

However, the evaporation from any commonly used pan cannot be directly considered as lake evaporation because the various physical factors which influence the evaporation process, and hence its magnitude, differ considerably between various pans and lakes.

References/Resources

Agency for International Development Congressional Presentations Fiscal Year 1979 and Fiscal Year 1980.

A.I.D. Project Papers and documentation for:
Barani Rainfed Land and Water Management - PAKISTAN
Resource Conservation and Utilization - NEPAL
Reforestation and Watershed Management - SRI LANKA
Citanduy River Basin Development - INDONESIA

"Resource Management for Rainfed Regions of West Pakistan", USDA/USAID, 1969.

A.I.D. Project Evaluation System (PES) April 1979 Project Assessment of the Citanduy River Basin Development Project - INDONESIA

USAID/Indonesia Memorandum "An Indonesian Watershed Program and USAID Involvement," Dr. Gerrit H. Argento, September, 1978.

The accurate value of evaporation for such an interval of time can only be obtained by means of a special survey to evaluate changes in heat storage and advected energy.

Seasonal variations in the lake to Class A pan coefficients are usually large enough to preclude the use of a constant value. The annual coefficients depend on climate and lake depth and range from 0.60 to 0.80. The average annual value of the Class A pan coeffficient to 0.70. The range for Australian sunken tank coefficient appears to be equally large.

The spatial variation in the lake to Class A pan coefficient is real and appears to be related to climate. In the U.S.A. the variation of the annual coefficient is from 0.60 in arid zones to near 0.80 over the moist east and west coast states. Geographic corrections of this nature could be used when applying U.S.A. results to other countries.

Annual evaporation from tanks with diameters greater than about 3.0 m and depth about 2.0 m approximates lake evaporation. Their data, without any considerable corrections, may be extended to small reservoirs 5-10 hectares in area and up to 5 m deep, when the tank and reservoir are located in open land under similar environmental conditions."

Potential Evapotranspiration

Evapotranspiration (ET) is the term that applies to the total water vapor exchange as a result of evaporation from surface of soil and vegetation (as for intercepted water) and from transpiration through the plant. The ET rate thus depends upon both the availability of water to the plant and the climatic demand for water. The evaluation could be simplified if calculations were made only of the rate to be expected from well-watered plants, i.e. "potential evapotranspiration."

The potential evapotranspiration (PET) concept was first proposed by Thornthwaite (1944,1948) in an effort to simplify calculation of water use by irrigated crops. After some minor revisions, the currently accepted definition is; "The rate of evaporation from an extended surface of a short green crop actively growing, completely shading the ground of uniform height, and not short of water".

The PET concept has been widely accepted, and it has stimulated a vast amount of research into evaporation from natural surfaces. There have been many applications in classification of climate, but the greatest interest has been in the development of PET estimates as a first step in estimating actual evapotranspiration. For this application, the initial PET estimates are adjusted to account for lack of water or failure of the surface conditions to meet the requirements of the definition.

The basic conditions that are required for PET are given in the definition. Specifying that the vegetation be low in height, actively growing and with complete canopy closure reduces the variability in the plant 'component of the hydrologic cycle. Variability in soil water is minimized by specifying that the soil be plentifully supplied with water. These conditions are precisely those to be encountered in virtually any arid zone irrigation project, once the crop canopies have closed, leading to Thornthwaite's (1944) original concept was that PET would be equal to consumptive use in irrigated agriculture.

The PET concept has also been severely criticized. W. C. Swinbank's (1965) discussion of Stanhill's paper on this topic is an example: "I would suggest to Dr. Stanhill tha the concept of potential evaporation is a useless one, in that it cannot be defined and cannot be measured, and that all he has said this afternoon reinforces this view." Stanhill (1973) concluded "Despite the manifold uses to which the concept of potential evapotranspiration has been put in the past, inherent contradictions in the multiplicity of definitions that have been put forward, make it one whose current necessity is open to considerable doubt."

Ward, R. C. 1975. Principles of Hydrology. Second Edition. McGraw-Hill. 367p.

These provide excellent summaries of a rich and varied literature on evaporation, and they are good sources for further reference and for applications.

The role of evaporation in the hydrologic cycle has held the interest of water managers for many years, as this process generates a direct loss of water that might otherwise be placed to a higher, more beneficial use.

The magnitudes of this loss can be considerable, especially in arid regions. The Arizona Water Commission (1975) places the annual evaporation from Lake Mead at 813,000 acre feet (1.003 x $10^9 m^3$). This volume is about 10 percent of the 1959-73 average annual flow of the Colorado River at Hoover Dam (7,989,000 acre feet. pr 9.854 x $10^9 m^3$). This volume is equivalent to a depth of 82 inches (2.1m) over the surface of Lake Mead. The annual evaporation from Lake Nasser, in contrast, has been estimated to be 24 x$10^9 m^3$, equivalent to 3m depth. This amounts to 25 percent of the annual flow of the Nile at Aswan Dam.

Further data on various annual evaporation totals are tabulated in Table 1. Note that only one of the reservoirs included in the list loses more water than the annual total of 84 inches (2.13m) lost by the Atlantic Ocean of Cape Hatteras, North Carolina.

The losses from free water in reservoirs are large, but the areas are not too great. The amount of water evaporated from various types of natural plant communities is also considerable. Data tabulated in Table 2 range from a depth equivalent of 10.6 inches in semi-arid grasslands up to 30 inches in moist coniferous forests.

The urge to put these "losses" to beneficial use in agriculture has been great. The various crops grown in the southwestern USA are tabulated in the Table 3, with regard to annual water requirements. These vary from somewhat less than 1 ft. up to 5 ft. per year. Much of the emphasis in watershed management research has been to develop ways to reduce the evaporation loss from natural plant communities in order to provide additional water for irrigation.

The magnitude of possible savings can be examined in Table 4, which summarizes the water losses from phreatophytes in various areas of the USA. Phreatophytes florish along streams, shorelines, and in floodplains where their roots have ready access to shallow groundwater. The heavy water consumption and limited value of phreatophytes have made them prime candidates for vegetation conversion schemes.

Our purpose is to examine the processes and measurement techniques for evaluating evaporation, now that we have reviewed data that illustrate the magnitude involved. The application of the evaporation data to watershed management problems will be carried out in a subsequent portion of the shortcourse.

Evaporation Principles

Evaporation of water in the hydrologic cycle consists of the change of state from liquid to vapor and the net transfer of this vapor into the atmosphere. The process occurs when some molecules of the liquid attain sufficient kinetic energy to overcome the forces of surface tension and escape from the surface of the liquid. To do so, the molecules must obtain energy from an outside source. This energy comes from solar radiation, sensible heat transfer from the atmosphere, or from heat advected into the water body by inflowing warm water. Because radiation is usually the dominant source of energy, evaporation is a function of latitude, season, time of day, and cloudiness.

Empirical models

A number of empirical models are used for estimating PET. The agreement between PET predictions by the more common models depends upon the conditions within the area of application as well as upon the care with which the calibration coefficients are fitted. Several of the more important methods will be discussed briefly here, but the original articles should be consulted for full details.

A Temperature Model. Thornthwaite (1948) recognized the strong correlation between radiation and mean air temperatures. He proposed a model relating PET directly to air temperature

$$PET = (d/360)(1.6)(10T/I)^a \quad g/cm^2 \ day \tag{4}$$

where

T is the monthly mean temperature (in ° C)
I is a heat index for the station, derived from longterm monthly air temperature.
a is a function of I
d is the daylength (number of hours)

The value of the annual heat index, I, is obtained by summing twelve monthly indexes $i = (T/5)^{1.514}$. The coefficient $a = C_1I^3 + C_2I^2 + C_3I + C_4$ where $c_1 = 6.75E - 7$, $C_2 = -7.71E - 5$, $C_3 = 0.01792$ and $C_4 = 0.49239$.

The term (d/360) in Equation (4) adjusts the estimated PET for deviations from a standard 12-hour day (d/12), and 30-day month (N/30), for a daily basis (1/N) where N is the number of days in the month. Values of d are available in the Smithsonian Meteorological Tables. The calculations are easily done with a hand calculator or with nomograms that have been developed (Palmer and Havens, 1958).

A Radiation and Temperature Model. The effect of temperature on the evaporation rate has been combined with that of solar radiation by Jensen and Haise (1963). Their model is:

$$PET = C_T(T - Tx)\, K{\downarrow}/L \quad g/cm^2 \ day \tag{5}$$

where

C_T is a temperature coefficient that is approximately equal to the reciprocal of the mean temperature.

T is the average daily temperature (°C)
Tx is a temperature coefficient
K↓ is the daily solar radiation (cal/cm^2 day)
L is latent energy of vaporization (≈585 cal/g)

The equation is deceptively simple, for the coefficients vary with elevation and atmospheric moisture content, as well as with temperature. The adjustments are summarized by Jensen (1966). The coefficient C_T can be estimated by

$$C_T = 1/27 + 7.3C_H \tag{6}$$

with

$$C_H = 50 \ mb/e_2 - e_1 \tag{7}$$

where e_2 and e_1 are the saturation vapor pressures at the mean monthly maximum and minimum air temperatures for the warmest month. Tx can be estimated as present, and the evaporating area will differ from the area of the ground. In general, the effective evaporating area of a vegetated surface is less than that of the underlying plane surface. Areas with ample subsurface moisture may behave as if they were partially wetted, depending upon the degree of saturation and whether or not vegetation is present. The wetted portion will vary from 1.0 for lakes and ponds, down to lower values that depend upon surface moisture and the density and type of vegetation. The vegetation density and degree of saturation of the surface and subsurface are particularly variable and difficult to measure in arid zones.

The ability of the atmosphere to accept water vapor, and the availability of water at the surface combine to produce evapotranspiration rates that are highly variable in time and in space. Our discussions, therefore, will consider first the evaporation of water from free water surfaces, (lakes, rivers, etc.), then the evaporation and transpiration from well-watered vegetation (irrigated crops, marshes, etc.), and finally the actual evaporation and transpiration from vegetation that has only a limited amount of water available within the rooting zone.

Evaporation from Lakes

The atmosphere plays a major role in the evaporation from free water surfaces. However, the properties of the evaporating body can have a secondary effect. These factors include salinity, depth and size.

Since the evaporation rate decreases about 1 percent for each 1 percent increase in salinity, seawater (average salinity of 3.5 percent) has an evaporation rate of about 3 percent less than that of fresh water. This is a negligible decrease for the purpose of most evaporation studies. In contrast, the depth of the water body can markedly affect the seasonal distribution of evaporation, although the annual totals are likely to be only slightly affected. While a shallow water body will approximately follow the air temperature, the thermal storage capacity of a deep lake causes it to be markedly cooler than the air in the summer and warmer in winter. A deep lake, therefore, will have its maximum evaporation during the winter months.

The shift in monthly evaporation with depth of water is strikingly demonstrated in Figure 1 (from Ward, 1975). The shallow reservoir has its peak evaporation in the warm summer months, while the deep lake has its maximum then.

The effect of lake depth on evaporation can be further demonstrated by some interesting lake evaporation data which have been recorded at two neighbouring lakes in Nevada. One of the lakes, Pyramid Lake, has a depth in excess of 61 m over much of its area while the other, Winnemucca, does not exceed 4.6 m in depth. Both lakes are approxiamtely at the same elevation; Pyramid Lake has a surface area of approximately 48,000 ha and Winnemucca 4,050 ha during the common four-year period over which observations were made. As shown in Table 5 the annual evaporation from both lakes was approximately the same but the seasonal patterns were reversed.

The relationship between the size of a water surface and the rate of evaporation from it has long been a subject of investigation. Figure 2 (from Ward, 1975) shows qualitatively how, with constant windspeeds, the rate of evaporation is related to the size of the evaporating surface and to the relative humidity. The reasons for this phenomenon are not difficult to understand. Thus, air moving across a large lake (see Figure 3, from Ward, 1975) may have a low water vapor content at the upwind edge; evaporation from the lake surface will gradually increase the water vapor content but, at the same time, there will be a reciprocal decrease in the rate of evaporation as the vapor 'blanket' increases in thickness. It is evident that the larger the lake, the greater will be the total reduction in the depth of water evaporated, although of course the total volume of water evaporated will almost inevitably increase with the size of water surface.

With other conditions remaining constant, the differences in evaporation rates from different-sized evaporating surfaces will be considerably affected by the huimidity of the 'incoming' air (see Figure 2.) If this is initially high, then clearly it will be modified only

The Penman model predicts the evaporation expected from an open water surface (E_0), rather than that from vegetation (PET). Penman related the two by an experimentally determined coefficient, k, ($PET = kE_0$) that varied under English conditions from 0.6 in winter to 0.8 in summer.

The weighting coefficient ($W = \Delta/(\Delta + \gamma)$) is the same as in the Priestley-Taylor model (Equation 8). The coefficient expresses the relative importance of the two terms that comprise the combination equation. The first term is primarily of radiation, and the second of aerodynamic processes. The temperature effect was illustrated previously in Figure 10 at both sea level and 2000 m elevation over a range of temperatures. At sea level, the relative weights of the radiative and the aerodynamic terms are approximately equal at 7°C. As temperatures rise above 30°C, the weight of the radiative term becomes greater than that of the aerodynamic term by a factor of 4 or more.

The model can be applied over any desired time period. With units above, and for input variables averaged over the period of a day (24-hours), the evaporation estimates will have units of g/cm^2 day, which is equivalent to evaporation in cm/day. The model is intended to yield mean daily estimates of evaporation, with the daily input variables being averaged from weekly or monthly meteorological records.

The wind function is an important component of the second term in Equation (9). The wind function depends upon the units specified, as well as upon the time period over which the estimates are being made. The original function was developed to estimate evaporation over day-long periods. Penman's (1948) wind function (adjusted to g/cm^2 day mb) was $f(u) = 0.035 \cdot (1 + 0.0098\ U_2)$, with U_2 being the total wind run (miles/day) at a height of 2m. This was revised slightly (Penman, 1956) to $f(u) = 0.035(0.5 + 0.01\ U)$. The coefficients are scaled for vapor pressure deficits in mm Hg, rather than mb. With U expressed in uits of km/day and vapor pressure in mb, Penman's original wind function becomes $f(u) = 0.02262(1 + 0.0061\ U_2)$ g/cm^2 day/mb.

Wind values are often measured at a height other than 2 m; these can be adjusted to the equivalent value at 2 m by multiplication with an adjustment factor. The approximate adjustment factor is $(2/z_a)^{1/6}$ where z_a is the actual measurement height (in meters).

Comparison of models

Inability to identify and develop a standard reference surface has limited tests and verification of the various PET models. There have, however, been quantitative comparisons of various methods against meaxurements from irrigated vegetation, and additional, more qualitative, comparisons among a number of methods without comparison against a standard.

Many of these studies have been carried out in humid areas with ample precipitation. Some of the studiess have been affected by selection of the model, or the size of the coefficients used. Not all of the experiments have proven useful in identifying the most general or most accurate PET estimators. We shall examine results from several studies that were carried out in arid areas.

Stanhill (1961) reported a test of eight methods of calculating potential evapotranspiration, with reference to actual losses from three lysimeters in an irrigated alfalfa crop. The data used covered 12 months (49 weeks) while the crop was fully developed. The methods used included measurements from a Class A evaporation pan, the temperature method of Thornthwaite, a solar radiation and air temperature method described by Makkink (1957), and the combination method of Penman.

The monthly comparisions indicated that the adjusted estimates (E_0) from the Penman equation gave the smallest coefficient of error, the highest correlation coefficient (r = 0.96) and the predictions nearest unity ($dE_0/dE = 1.03$). The Makkink and Thornthwaite methods gave similar results in that the correlation coefficients were high (r = 0.95, 0.94, respectively), but the model

The basic calculation of E_L is :

$$E_L = kp \times Ep \tag{3}$$

where Ep is the measured pan evaporation and kp is a pan coefficient where $kp = E_L/Ep$. The development of coefficients for various environments and for various types of evaporation pans has been discussed thoroughly by Hounam (1973). 73). He concludes that simple pan coefficients (E_L/Ep) can be used for annual totals of evaporation, but more thorough considerations are required for estimating seasonal E_L values.

The basic evaporation pan that we shall consider is the USA Class A pan. The pan is circular, 121.0 cm (47.5 in.) in diameter and 25.4 cm (10 in.) deep, mounted on a wooden open frame platform so that the pan base is about 5-10 cm (2-4 in.) above the ground. It is normally constructed of galvanized iron, but other more durable metals or fibreglass have been used (presently monel metal is recommended). The pan is filled to within 5.1 cm (2 in.) of the rim, and measurements may be made by hook or fixed point gauge. There are a variety of evaporation pan designs that are in routine use around the world. The more common ones are listed in Table 6.

The factors that affect the evaporation rate of the pan include radiation exchange characteristics (albedo, temperature), wind exposure, size of evaporating pan surface, and nature of surroundings. In addition, the relationship to a given lake will be influenced by the size and the depth of the lake.

The Class A pan is freely exposed to the environment, and it consequently evaporates more water than lakes, especially in warm dry climates. Hounam (1973) has summarized available data on Class A pan coefficients in Table 7. His analysis can be consulted for details and for the primary references. The coefficients range from 0.60 at Lake Mead in Western Arizona up to 0.82 at Lake Mendota in Wisconsin and 0.86 at Lake Eucumbene in New South Wales, Australia.

The annual lake evaporation totals in Arizona can be estimated using evaporation pan data. The pan evaporation totals are shown in Figure 6; they range from 380 cm in the extreme west to less than 190 cm in the northeast. The limited number of observation pans requires considerable conjecture to interpolate the results. The pan coefficients used by the U.S. Weather Bureau are mapped in Figure 7 (U.S. Dept. Commerce, 1968). The coefficients are associated with exposure; they range from 0.60 in the hot dry west to 0.70 in the cool, more humid central mountain region.

The estimated lake evaporation across the state is shown in Figure 8, based upon the pan evaporation in Figure 6 and the pan coefficients in Figure 7. The annual values range from 230 cm in the west down to 127 cm in the northeast. The maximum values are in the arid western lowlands, and the minimum values are in the higher, cooler northeast.

Although Hounam (1973) should be consulted for detailed applications, his following conclusions apply to the pan method:

"The simple lake to pan coefficients, determined as (E_L/E_p), can only provide estimates of lake evaporation with reasonable accuracy on an annual basis.

When pan measurements are used to compute lake evaporation for a particular year or season or to provide a mean monthly estimate, corrections have to be introduced to account for those parameters which have an important influence on lake and pan evaporation, such as net heat advection, change in heat stored and the surface area. This must be done for all types of pan at present in use for measuring evaporation.

No general technique has as yet been developed for accurately estimating the lake evaporation from pan evaporation data for short periods of time such as a week or a 10-day period.

occurring in midsummer. The adjusted pan evaporation rate of 8.8 mm/day fell midway between the two highest formula estimates at the summer peak.

Both the Priestley-Taylor and the Thornthwaite estimates were low in comparison with the above three. The Thornthwaite method also shifted peak evaporation rates from June into July. This phase shift, noted many times by other authors, is associated with heat storage in the soil during the warming season (spring and early summer).

The monthly and annual means by the various methods are tabulated in Table 8 with totals in cm for month or for year. The Penman estimatees exceed adjusted pan evaporation slightly on an annual basis. Otherwise, the order is the same as for the mid-summer period. The largest estimate from a formula method (Jensen-Haise) is about twice that of the lowest (Thornthwaite).

Considerable variability is evident among the selected methods in Figure 11 and Table 8. The Penman method, as pointed out by Doorenbos and Pruitt (1975), varies with such factors as distribution of wind between day and night, and with choice of wind function. The Thornthwaite estimates demonstrate the empirical temperature method's shortcomings in arid climates. Rates from the Jensen-Haise method are higher than the adjusted pan evaporation (open water) which itself is directly affected by the selection of a pan coefficient.

The lack of a reference standard makes comparison of methods difficult. Even when evaporation data is available from research plots, the evapotranspiration rate is influenced by the physiological condition of the vegetation as well as by the size of the plot. These factors tend to support the view that the evaporation pan is the best possibility for a standardized estimate of potential evapotranspiration. The configuration of the pan and condition of exposure can be carefully defined, and the development of reasonable procedures for evaluating pan coefficients is well along (Doorenbos and Pruitt, 1975). The pan method holds great promise for obtaining evaporation estimates that can be compared from one place to another.

The annual PET totals for a specific site such as Tucson, Arizona, are of general interest, but they are not necessarily indicative of actual evapotranspiration, even from irrigated crops that meet the conditions of the PET definition. The period during which the plants meet the PET conditions is one reason for discrepancy. Most irrigated crops do not maintain closed canopies and full growth throughout the year, even in warm regions. Grains, for example, cease growth at maturity, and a considerable period may elapse in the spring before crown closure occurs in some crops. This was clearly illustrated earlier in Figure 9. Further, below-freezing temperatures effectively limit transpiration. Tucson, Arizona, for example, has a season from Feb. 16 to Nov. 28 between the normal occurrence of the last severe frost (-2.2°C, or 28°F) in the spring, and the first in the fall. Yuma, in the southwest corner of Arizona, is normally frost-free throughout the year, while Flagstaff, in the central mountains, normally goes only from May 22 to Oct. 10 between -2.2°C (28°F) frosts. Regional evapotranspiration estimates should be adjusted to predict totals for the frost-free season.

Actual Evapotranspiration.

Actual evapotranspiration (ET) obviously could originate from either of the previously discussed situations: lake evaporation and potential evapotranspiration. This discussion will generalize the solutions for evaluating water losses to include the conditions when the supply of water is limited. This condition makes the problem much more difficult. The methods to be described are also applicable for use in measuring E_L or PET. The methods will be considered in order of increasing precision and complexity. The first will be adjustment of PET estimates, next the application of the water balance, and finally evaluation of the energy balance.

Adjustments to PET

The most popular method of computing actual evapotranspiration is through the calculation of potential evapotranspiration. If there is abundant moisture in the soil, the two rates are equal.

Problems in utilizing the PET concept are related to the imprecise nature of the definition, leading to errors in application and misplaced expectations. There have also been failures to fully appreciate short-comings inherent in the many different models that have been proposed for estimating PET. The extreme climatic conditions of arid environments have contributed to these problems. However, when vegetation is irrigated, essentially all variability associated with availability of water is eliminated. Also the effects of vegetation upon the evaporation rate from well-watered surfaces are essentially similar. This has led to a vast amount of experimental work designed to estimate evaporation solely from properties of the atmosphere.

As the PET concept has become accepted, a variety of methods have evolved to provide the desired estimates. These models are based almost entirely upon atmospheric variables, since the PET definition removes the greater source of variability associated with the availability of water.

The wide variety of models proposed for evaluating PET will not be reviewed in detail here. Doorenbos and Pruitt (1975), for example, identify 31 formulas that estimate evapotranspiration from irrigated crops; nine of the formulas estimate PET. Nearly all of these formulas are empirical, and depend upon a known correlation between evapotranspiration and one or more climate variables such as temperature, radiation, humidity, and wind speed. Other formulas have related evapotranspiration to direct observations from evaporation pans. Almost all of the formulas contain empirical coefficients that calibrate the models for conditions of the regions in which they are used.

There have been many comparisons of different methods for estimating PET, but there is no reference standard to determine the "true" PET value. The lack of a suitable reference has made it difficult to test the various approaches to estimating PET.

Pan evaporation models

A possible standard for PET is the evaporation rate (E_p) that is measured directly with an evaporation pan. As in the application to lake evaporation, the basic model is simple: PET = $K_p E_p$ with the constant K_p to be determined empirically. Note that the coefficient K_p differs from the k used in Equation (3) to relate E_p and E_L.

Stanhill (1965) recommends the Class A evaporation pan as the best method of estimating potential evapotranspiration, given consideration of accuracy, simplicity and cost. Pruitt (1966) reviewed many studies and concluded that pan evaporation could give an excellent estimate of evapotranspiration from irrigated grass. He emphasized the necessity to standardize the exposure of the pans, because rates in agricultural areas may differ as much as 40 percent between dryland sites and irrigated field sites. He further suggested a reduction in the order of 0.75 would bring losses from dryland Class A pans down to the levels of those located within irrigated fields.

The pan design also influences the evaporation rate. The exposed Class A pan of the U. S. Weather Bureau evaporates at a higher rate than do various sunken or insulated models. Guidelines for choice of an appropriate reduction coefficient are given by Doorenbos and Pruitt (1975) for a variety of climatic and site conditions.

The relation between the adjusted evaporation rates and the evapotranspiration from irrigated crops is quite good in temperate regions. The ratio of PET to E_{pan} for Class A pans over a range of sites was about 0.8 for grass and grass-clover mixtures and 1.0 for alfalfa (Pruitt, 1966). Doorenbos and Pruitt (1975) point out that pan exposure errors increase in arid climates, especially in windy regions, and suggest that other methods, such as those based upon radiation, may be preferable for truly desert areas. They give excellent application guidelines for the pan method in many types of climates. Note that the coefficient can vary markedly with stage of vegetation. This is shown in Figure 9 for corn (from Dunne and Leopold, 1978).

The water balance

A water balance can be developed for large basins by measurements or estimates of the gains and losses. More accurate results are possible using small experimental catchments in which detailed measurements are made of hydrological variables. If the water balance equation $P - Q - E - \Delta S - \Delta G = 0$ (where P is precipitation, Q is streamflow, E is actual evapotranspiration, and ΔS and ΔG are changes in soil moisture and groundwater storage respectively) can be solved, then it is probable that the values of the individual components of that balance are accurate.

Clearly, this may not be so if discrepancies in the assessment of individual variables are fortuitously complementary, although this source of error can usually be guarded against by making specimen water balance calculations for different time periods within the same run of data. Since precipitation, streamflow, soil moisture, and groundwater measurements can be made with a greater accuracy than the corresponding estimations of evaporative loss, the value of E which consistently gives the best result in the water balance equation is the most 'suitable'.

The water balance approach need not be restricted to use only on watersheds. Indeed, the basic observations with the evaporation pan are specialized water balance measurements. An estimate of evapotranspiration can also be obtained by calculating the partial water balance for the soil profile, often within the context of an experimental plot study. The important work done by Thornthwaite on the climatic water balance substantiated the close relationship between P, E, and ΔS. An approach through soil moisture measurement, and particularly the determination of successive soil moisture profiles, is attractive because, within the soil profile one can obtain a direct measure of the amount of water withdrawn by the vegetation cover. The repeated soil moisture measurements that are needed to obtain an estimate of ΔS are now routinely and accurately obtained with neutron probes that can be repeatedly returned to the same sampling point.

The concept of the soil moisture balance and the evaporation pan are combined in the lysimeter. Lysimeters are confined blocks of soil that facilitate measurements of moisture change. Vegetation can be grown within the confined soil volume so a precise measurement can be made of moisture changes.

Two main types exist:- the earliest designs, called "evapotranspireters", maintained moist PET conditions within the soil-filled container. The moisture losses could be evaluated by measuring the water added to restore the water level, or by measuring the amount needed to bring the soil profile back to field capacity by subtracting drainage out the bottom from the input quantity. The more recent designs are essentially sealed except at the top, and the weight change is monitored continuously by weighing.

In order to extrapolate lysimeter measurements to the surrounding vegetation, the soil profile, root development, and moisture conditions should be the same within and without the tank. The type, height and density of the vegetation growing on the lysimeter must likewise match that of the surroundings. The weighing lysimeter is suited to a range of conditions and some designs permit precise measurements.

The neutron probe and the weighing lysimeter were used by Sammis and Gay (1979) in a study of year-long transpiration in a creosotebush community near Tucson. Primary measurements were made with a weighing lysimeter containing a large creosotebush. The water budget method was used to evalute evaporation from bare soil plots and evapotranspiration from a creosotebush community. Creosotebush was the dominant shrub, with paloverde (Cercidium microphyllum) and bursage (Ambrosia deltoidea) also present on the site.

A monolith lysimeter was constructed beneath a creosotebush, selected for its typical size, shape, condition and relative proximity to neighboring shrubs. The lysimeter was 4 m in diameter and 1 m deep. Lysimeter weight changes were measured by a commercially available strain-gauge capable of detecting a weight change of 2.36 kg, equivalent to 0.19 mm of water over the 12.57 m^2

$$Tx = -23 + C_H^2 + 750\ C_T$$

for those areas with $C_H < 2.8$. For actual calculations,refer to Jensen and Haise (1963). As an example, the coefficients at Tucson, Arizona (elevation 788m, July maximums of 36.9 °C and minimums of 23.3 °C) are $C_T = 0.027/°C$, $Tx = -3.59$ °C.

A Net Radiation Model. The Priestley and Taylor (1975) model focuses upon available energy ($Q^* + G$) as the primary factor controlling potential evapotranspiration from well-watered vegetation. Net radiation (Q^*) is used to represent available energy because the storage term (G) is relatively small at any time, and it is generally negligible when averaged over a 24-hour period. Net radiation is now being measured at a number of locations; it can also be estimated rather easily for those areas where measurements are lacking.

The Priestley-Taylor model is

$$PET = \alpha WQ^*/L \qquad (8)$$

where α is an empirical constant ($\alpha = 1.26$), L is the latent heat of vaporization and W is a temperature-dependent weighting factor. The flux density of net radiation (Q^*) is expressed cal/cm^{2}day.

The weighting factor W is equal to $\Delta/(\Delta + \gamma)$, where Δ is the slope of the saturation vapor curve (in mb/°C) at air temperature Ta, and γ is the psychrometric constant (mb/°C). Δ can be readily calculated from tabulated values of saturated vapor pressure (e_s, in mb) as a function of temperature (see, for example, the Smithsonian Meteorological Tables). The psychrometric constant, γ, has a nominal value of about 0.66 mb/°C. This varies with air pressure, p, in the ratio p/p_o where p_o is sea level pressure ($p_o = 1013.25$ mb). W thus varies with both temperature and with pressure (Figure 10). Typical sea level values of W are 0.55, 0.68, and 0.78 at temperatures of 10°, 20°, 30°C, respectively.

It is interesting to note that since Q^* is linearly related to $K\downarrow$ ($Q^* = a + bK\downarrow$, Gay, 1971), both the Priestley-Taylor and the Jensen-Haise models have the same basic form: $PET = \phi K\downarrow$ where ϕ represents the fraction of solar radiation transformed to net radiation, and ultimately, into evapotranspiration.

The Combination Model. The combination model of Penman (1948) is probably the most widely known PET estimator. In contrast to the pan observations and the empirical models, the Penman model is based upon a simplified radiation budget that has been combined with an aerodynamic analysis. The fundamental basis of the model gives it some generality in application. It has been applied in a wide range of conditions.

Penman's model can be written (after Doorenbos and Pruitt, 1975) as

$$E_o = W \cdot (Q^* + G)/L + (1 - W) \cdot f(u) \cdot (e_s - e) \quad \text{g/cm}^2 \text{ day} \qquad (9)$$

where

E_o is flux density of potential evaporation based upon open water (g/cm^2 day).
W is a dimensionless weighting factor that accounts for effects of temperature and pressure (see Figure 10).
Q^* is the flux density of net radiation (cal/cm^2 day).
G is the change in stored thermal energy, expressed as a flux density (cal/cm^2 day).
L is latent heat of vaporization (585 cal/g at 21.8°C).
f(u) is a wind function that approximates the diffusivity of the atmosphere near the ground (g/cm^2 day), and
$e_s - e$ is the vapor pressure deficit of the atmosphere at 2 m height (in mb).

In practice, two psychrometers are used to measure T_a and e at two levels in the air above but near the evaporating surface (which, by substraction, yield ΔT_a and Δe). Direct measurements are made of net radiation and changes in stored energy, and then Equations (12, 13) are solved for LE.

A recent report by Gay and Fritschen (1979) compares Bowen ratio estimates against constant level lysimeter estimates of evapotranspiration from saltcedar.

The Bernardo lysimeter site was selected for the energy budget measurements. Six constant-level lysimeters had been established in 1961 by the U. S. Bureau of Reclamation in an expanse of saltcedar on the floodplain of the Rio Grande, about 50 miles south of Albuquerque. The Bureau operated the lysimeters continuously from 1962-1968 (U. S. Bureau Reclamation, 1973), and has maintained them for intermittant measurements since that date. The lysimeters are equipped with pumps that maintain the water level at a constant setting. The mean depth to water was 154 cm during the period of our measurements, both within and without the lysimeters. Meteorological instrumentation was established above the saltcedar in the vicinity of the lysimeters. The saltcedar was about 3.15 m. tall. Though the stand was extensive, the canopy was sparse.

Instrumentation was similar to that used elsewhere for energy budget measurements (see Gay, 1973, among others). Net radiation was measured above the canopy with two net radimeters, and a soil heat flux plate within 3 cm of the surface provided an estimte of the changes in stored energy in the soil. Differential psychrometers were used to measure dry-bulb temperature and vapor pressure differences between two levels above the canopy. The psychrometer employed a reversing mechanism to exchange the sensors between levels in order to eliminate small biases that might otherwise affect the results. Wind velocities were measured above the canopy. The instruments were recorded periodically on a digital data system. The article should be consulted for a full description of the instrumentation and experimental design.

The diurnal energy balance for a single day is shown in Figure 13 at two different points over the saltcedar. The components of the energy balance, Equation 11, are identified in the Figure and plotted as rates of energy transfer (cal/cm^2 min). The daily sums of the energy budget components at the two saltcedar sample points are tabulated in Table 9. The latent energy totals can be converted to depth equivalent of evaporated water by division with the latent heat of vaporization (E = LE/L). The daily LE totals (in mm) are compared with the direct measurements from the four lysimeters in Table 10. The paper should be consulted for full analyses, but for our purpose it is sufficient to note that the five-day energy balance mean evaporation of 8.2 mm/day compares closely with the lysimeter mean of 7.9 mm/day.

Given the difference in conditions at the Bowen ratio sites and on the lysimeters, the agreement between the two methods was excellent. This reassuring agreement between the energy budget analysis and lysimeter mesurements adds confidence to the long (15 year) record obtained by the U. S. Bureau of Reclamation at the Bernardo experimental site. The agreement also substantiates the usefulness of the mobile, although more tedious, energy budget method for estimating evapotranspiration from riparian sites in arid zones.

estimates were considerably lower than actual evapotranspiration (δ PET/dE = 0.67, 0.68, respectively). The direct measurement of open water evaporation with the Class A evaporation pan had a similar degree of suitability but with an over-estimate ($dE_p/dE = 1.43$, $r = 0.95$). Stanhill concluded that the Penman method was the most satisfactory of the ones tested.

Cruff and Thompson (1967) compared a number of methods for estimating potential evapotranspiration in the Southwest, using mean monthly data (10 years of record) from U. S. Weather Bureau. Their standard of comparison was lake evaporation, which was estimated from evaporation pan measurements that were adjusted for exposure (the adjustment coefficients ranged from 0.60 to 0.78). The methods tested included the temperature methods of Thornthwaite, the temperature plus solar radiation method of Lane (1964) for estimating lake evaporation (E_L) and the U. S. Weather Bureau method. The Lane method is of the basic form of the Jensen-Haise model, and the U. S. Weather Bureau method is a minor variant of the Penman combination method.

The combination method gave the best results of the ones tested. The agreement between mean monthly E_L and lake (adjusted pan) evaporation was quite close, being 1.06 for the 7 sites that had adequate data. Other methods with smaller data requirements were tested at as many as 25 sites. Results from the Thornthwaite method were much lower (0.61) than the adjusted pan evaporation at 25 sites; results at 22 sites from the temperature plus solar radiation method of Lane were markedly higher (1.15).

Van Bavel (1966) compared Penman's method with lysimeter measurements of evaporation from open water, saturated soil, and irrigated alfalfa at Phoenix, Arizona. He used a revised wind function to estimate hourly and daily evaporation rates. For 13 days, the ratio of E_0 to measured evaporation was 1.04, leading Van Bavel to conclude that irrigated alfalfa exhibited essentially no stomatal resistance since it transpired near the potential rate. Further, he concluded that the Penman method satisfactorily evaluated the advective conditions that commonly occur in irrigated fields within arid areas.

PET Examples.

The variability between methods of estimating PET at a single point can be examined with reference to Tucson, Arizona.

The published temperature, wind, humidity and pan evaporation data at Tucson, Arizona, augmented by solar radiation data, were used to estimate PET by the various methods for the 10-year mean 1966–1975.

The net radiation values needed for the Penman and the Priestley-Taylor models were estimated from incoming solar radiation using the procedures of Doorenbos and Pruitt (1975). They first reduce the incoming solar for an assumed albedo of the hypothetical crop canopy (here, $\alpha = 0.25$). They next estimate the longwave component of net radiation with reference to percent possible sunshine and the temperature and the moisture content of the air. The percent possible sunshine was evaluated from average sky cover. Refer to Doorenbos and Pruitt (1975) for the details of the computations.

The Penman estimates were based on Equation 9, with Doorenbos and Pruitt's (1975) wind function: $f(u) = 0.027\ (1 + 0.01\ U_2)\ g/cm^2$ day. The other methods used the formulas as defined earlier; the adjusted pan evaporation is based upon a pan coefficient of 0.67 for the Tucson area (see Figure 7).

The mean monthly rates (mm/day) are plotted in Figure 11. Several methods (Jensen-Haise, adjusted pan, Penman) appeared reasonably consistent. The unadjusted pan evaporation rates were in the order of 150 % of the PET values predicted by this group. The Jensen-Haise method predicted maximum values of 9.9 mm/day during the midsummer months. The Penman estimates were the next highest of the formula methods; this method predicted 8.0 mm/day, with the evaporation peak also

TABLE 3. VARIATIONS IN CONSUMPTIVE USE BY CROPS

(from The Water Encyclopedia, 1970, D. K. Todd, Editor)

Crop	No. of tests	Range in water requirements, ft.
A. FARM CROPS IN THE SOUTHWEST		
Alfalfa	369	3.47-5.08
Rhodes grass	12	3.49-4.43
Sudan grass	25	2.88-3.15
Barley	3	1.24-1.83
Oats	2	1.90-2.09
Wheat	46	1.46-2.24
Corn	42	1.44-1.99
Kafir	16	1.32-1.54
Flax	3	1.23-1.59
Broomcorn	9	0.97-1.15
Emmer	6	1.19-1.87
Feterita	8	0.97-1.10
Millet	5	0.91-1.09
Milo	35	0.96-1.67
Sorghum	34	1.69-2.09
Cotton	103	2.35-3.51
Potatoes	12	1.59-2.04
Soybeans	36	1.66-2.81
Sugar beets	5	1.77-2.72
Sugar cane*	41	3.48-4.56
B. VEGETABLE CROPS IN THE SOUTHWEST		
Beans, snap	9	0.83-1.44
Beets, table	28	0.87-1.37
Cabbage	21	0.94-1.49
Carrots	6	1.27-1.60
Cauliflower	6	1.43-1.77
Lettuce	49	0.72-1.35
Onions	4	0.73-1.52
Peas	8	1.21-1.56
Melons	3	2.48-3.40
Spinach	12	0.80-1.07
Sweet potatoes	3	1.77-2.25
Tomatoes	17	0.95-1.42

*Not commonly produced in the Southwest.

TABLE 4. PHREATOPHYTE AREAS AND THEIR CONSUMPTIVE USE IN SELECTED WESTERN STATES

(from The Water Encyclopedia, 1970, D. K. Todd, Editor)

State	Area (Acres)	Annual use (Acre-feet)
Arizona	405,000	1,280,000
California[1]	317,000	1,150,000
Colorado[1]	737,000	1,056,000
Idaho	500,000	1,000,000
Montana	1,600,000	3,200,000
Nebraska[1]	515,000	709,000
Nevada	2,601,000	1,500,000
New Mexico	300,000	900 000
North Dakota	1,035,000	1,660,000
Oregon[1]	40,800	21,200
South Dakota	850,000	1,240,000
Texas[1]	262,000	436,500
Utah	1,200,000	1,500,000
Wyoming	527,000	1,100,000
Total (approximate)[2]	11,090,000	16,750,000

[1] Partial data, from published reports on areas within the State.

[2] Partial data.

When moisture supply becomes limiting, the computed potential rate is modulated by a factor that depends upon the amount of water in the soil. The relationship can be expressed as (Dunne and Leopold, 1978)

$$AET = PET \times \underline{f}(AW/AWC) \tag{10}$$

where AET and PET = the actual and potential rates of evapotranspiration

$\underline{f}(\ )$ = some function of the term inside the parentheses

AW = the available soil moisture = (soil moisture content - permanent wilting point) x rooting depth of vegetation (cm)

AWC = the available water capacity of the soil = (field capacity - permanent wilting point) x rooting depth of vegetation (cm).

The form of the function that modulates PET in response to limiting water has received much study. Veihmeyer and his co-workers conducted a series of experiments in California and concluded that evapotranspiration proceeds at the potential rate until soil moisture is depleted to the permanent wilting point. Plants then wilt and evapotranspiration rates fall sharply to near zero. Thornthwaite and Mather, working on a loam in Nebraska, found that the ratio of actual to potential evapotranspiration decreases as a linear function of the amount of available water (see Figure 12). Other workers have proposed various compromises between these two extremes, most of them suggesting that evapotranspiration occurs at close to the potential rate until a considerable proportion of the available water is depleted, after which the actual evapotranspiration rate falls rapidly. One such example (Pierce) is incorporated in Figure 12(a) (from Dunne and Leopold, 1978).

The accuracy of these approximations will vary with soil type and rooting characteristics. In a sandy soil, for example, plants with a dense root system can withdraw water rapidly from the pores, and evapotranspiration may proceed at close to the potential rate until soil moisture content is close to the wilting point. In a clay-rich, loamy soil, water is held more tightly at a given soil moisture content, and movement of water to the roots is slow. Under such circumstances moisture supply to the roots will not keep up with potential rates of loss, and actual evapotranspiration rates will decline throughout most of the range of available water. Holmes (see Figure 12(b)) presented a schematic relationship between actual and potential rates of evapotranspiration over the range of available water capacity for three soil textures. This relationship can be compared with the results of previously mentioned workers in Figure 12(a). The comparison shows that the Veihmeyer and Thornthwaite models should be adequate approximations for sandy and clay-rich soils, respectively. In the absence of detailed measurements, an estimation of the appropriate relationship for intermediate soils involves a good deal of guesswork. The situation is further complicated by the intensity of the evaporative demand. Under low demand, soil moisture may be able to move to the root system rapidly enough to maintain transpiration at the potential rate. If the demand increases, the soil moisture movement may not be rapid enough to do this.

In view of the difficulties of applying the previously mentioned results to soils for the solution of particular problems, several simpler relationships have been used with some success. Ideally they should be checked under the field conditions to which they are to be applied by making measurements of actual soil moisture losses, but in practice this is not usually done. Often the hydrologist will use two extreme estimates and calculate the actual water loss under both conditions. Frequently, the results do not differ by a large amount.

The application of the method is simple. The PET estimates are used to reduce the amount of water remaining in the soil. Eventually, a point is reached, (based on the function used) when actual ET falls below PET. The ET becomes reduced further and further below PET as more and more of the soil water is extracted. Eventually, precipitation should recharge the soil profile and actual ET, given that soil water is freely available, will again equal PET.

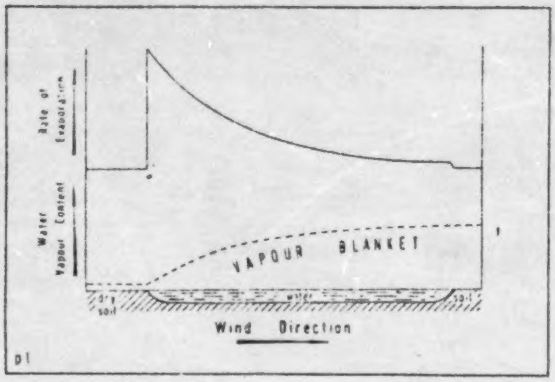

Rate of Evaporation
Water Vapour Content
VAPOUR BLANKET
dry soil
water
soil
Wind Direction
p1

Figure 3 A simple illustration of the increase in humidity and decrease in evaporation as air moves across a large water surface (Ward, 1975).

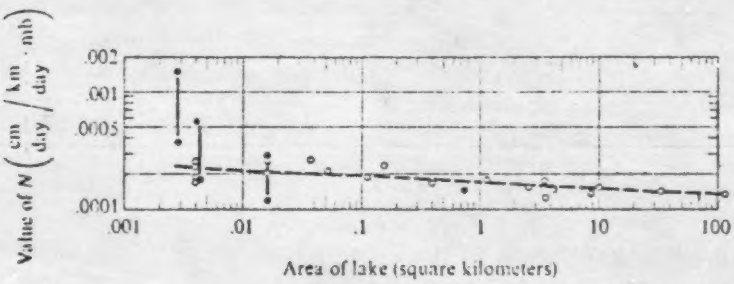


Figure 4. Mass-transfer coefficient, N, as a function of lake area. Open circles are data from lakes in the southwestern U.S.; solid circles are for Indiana and western Canada; dashed line is Harbeck's mean relationship.

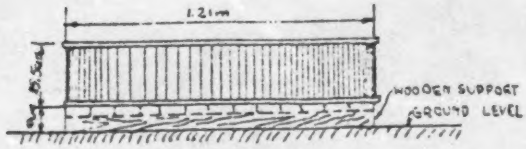

1.21m
25.5cm
WOODEN SUPPORT
GROUND LEVEL

Figure 5 Side view of Class A pan (Hounam, 1973).

surface area. The lysimeter weight change was recorded weekly. Water loss on the bare soil and the vegetated plots was determined by a water balance where:

$$\text{Evapotranspiration} = \text{Precipitation} \pm \text{Change in soil moisture.}$$

This simple formulation applies where deep drainage and runoff are negligable. At this experimental site, all changes in soil moisture during the study period were confined to the top meter of soil. Further, no measurable runoff occurred through flumes on the watershed.

The neutron probe was used to measure changes in soil moisture content at the experimental site. One set of four access tubes was located in a bare soil plot in an open area that was isolated from shrub roots by a plastic barrier. Four additional sets, each containing four access tubes, were located within the surounding creosotebush stand. The soil moisture content at each access tube was determined at 25 cm intervals to a depth of 2 m, and meaurements were normally made every 2 weeks.

The one-year water loss from the weighing lysimeter was 259mm, compared to neutron probe estimates of 242 mm from an adjacent stand of creosotebush, and 231 mm from bare soil plots. The three loss estimates were in good agreement with measured annual precipitation of 234 mm. There was no deep percolation or surface runoff during the year, and all losses were by evapotranspiration.

This study is one of the few applications of lysimeter to measurements of wildland ET. There are numerous reports of their use in irrigated agriculture, however.

The energy balance

The balance of energy gains and losses to an area can be measured more easily than the moisture fluxes in certain experimental situations, thus providing a means for evaluating evaporation from energy measurements. This provides a powerful tool that can be used for experimental work on evaporation and to cross-check evaporation estimates derived from other techniques.

The basic energy budget model is described in many different texts. It sums the energy available from net exchange of radiation (Q^*), changes in stored energy (G), convection (H) and latent energy (LE):

$$Q^* + G + H + LE = 0 \qquad (11)$$

The energy budget expressed in flux density units (e.g., cal/cm^2 min or W/m^2) applies to periods of any length. The flux polarities may be either positive or negative, and we use the common convention that fluxes directed to the surface are positive, and those away from the surface are negative.

The basic Bowen ratio model is :

$$LE = (Q^* + G) / (1 + \beta) \qquad (12)$$

where $\beta = H/LE$. β was estimated from measurements of dry-bulb temperature differences (ΔT_a) and vapor pressure differences (ΔE) at two levels above the vegetation with the model

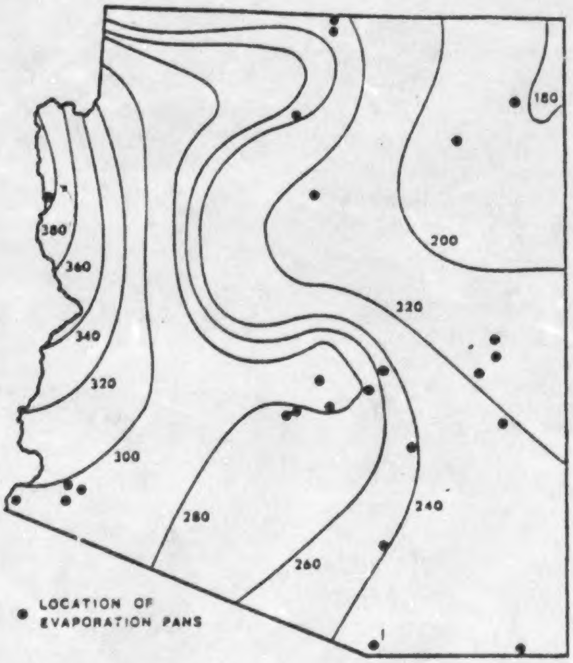
$$\beta\beta = \gamma(\Delta Ta/\Delta e) \qquad (13)$$

where γ is the psychrometric constant (γ is approximately equal to 0.66 mb/°C) at sea level pressure ($P = P_o$). γ varies with air pressure in the ratio P/P_o, and so γ may drop to values near 0.55 at higher elevations.

Table 7

Annual coefficients for lake to Class A pan evaporation (E_L/E_P) (Hounam, 1973).

Location		Surface area in square kilometres	Average depth in metres	Pan coefficient	Observation period	Control method	Reference
Lake Elsinore	California	22.27	3.05	0.77	1939-41	Water budget	Young (1945)
Red Bluff Resv.	Texas	-	-	0.68	1939-47	Water budget	Kohler (1954)
Lake Okeechobee	Florida	1813.0	3.05	0.81	1940-46	Water budget	Kohler (1954)
Lake Hefner	Oklahoma	8.82	7.93	0.68	1950-51	Water budget	Sellers (1965)
Felt Lake	California	0.26	6.40	0.77	1955	Water budget	Kohler (1958)
Lake Colorado City	Texas	8.29	4.88	0.72	1954-55	Energy budget	Kohler (1958)
Lake Mead	Arizona	512.82	53.68	0.60	1952-53	Energy budget	Kohler (1958)
Lake Mendota	Wisconsin	39.11	12.20	0.82	27 years	Energy budget	Sellers (1965)
Salton Sea	California	777.01	7.32	0.52	1961-62		Sellers (1965)
Silver Lake	California	51.80	0.91	0.61	1938-39	Water budget	Kohler (1958)
Fort McIntosh	Texas	-	-	0.79	1950-51		Kohler (1958)
Kempton Park	London	0.16	7.01	0.70	1956-62	Water budget	Lapworth (1965)
Lake Eucumbene	N.S.W.	98.16	23.77	0.86	1962-64	Bulk aerodynamic	Snowy Mountains Hydro-elec. Authority (unpublished)



AVERAGE ANNUAL PAN EVAPORATION
(Centimeters)

Figure 6 Average annual pan evaporation in Arizona (adapted from U.S. Dept. Comm. 1968).

TABLE 1. RESERVOIR EVAPORATION AT SELECTED STATIONS IN THE UNITED STATES

(from D. K. Todd, Editor, The Water Encyclopedia. 1970)

[Mean monthly computed values in inches]

Station	Month												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	An
Ariz., Yuma	3.9	4.6	6.5	8.0	9.8	11.5	13.4	12.9	10.7	8.0	6.1	4.5	
Calif., Sacramento	0.8	1.4	2.5	3.6	5.0	7.1	8.9	8.6	7.1	4.8	2.6	1.2	
Colo., Denver	1.6	1.8	2.5	3.7	5.0	7.4	8.8	8.4	6.7	4.6	3.0	1.9	
Fla., Miami	3.0	3.4	4.1	4.9	5.0	4.8	5.3	5.1	4.3	4.1	4.3	2.7	
Ga., Macon	1.7	2.2	3.1	4.3	5.1	6.2	6.3	5.8	5.2	4.2	2.8	1.8	
Me., Eastport	0.8	0.7	0.9	1.1	1.4	1.7	2.0	2.1	2.0	1.6	1.1	0.7	
Minn., Minneapolis	0.3	0.4	0.9	1.7	3.2	4.4	6.0	5.8	4.6	3.0	1.3	0.4	
Miss., Vicksburg	1.3	1.9	2.9	4.2	5.0	5.7	5.8	5.5	5.2	4.4	2.9	1.6	
Mo., Kansas City	0.9	1.1	1.7	3.1	4.4	6.1	8.0	7.8	6.0	4.5	2.5	1.0	
Mont., Havre	0.5	0.5	1.1	2.5	4.5	6.1	8.2	8.3	5.6	3.3	1.5	0.7	
Nebr., North Platte	0.8	1.1	2.2	3.7	5.0	6.5	8.6	8.4	6.9	4.6	2.6	1.1	
N. Mex., Roswell	2.1	3.2	4.9	6.8	8.3	9.8	9.4	8.3	6.9	5.5	3.5	2.5	
N. Y., Albany	0.6	0.7	1.1	2.0	3.2	4.3	5.2	4.7	3.4	2.4	1.4	0.8	
N. Dak., Bismarck	0.4	0.5	1.0	2.3	4.0	5.3	7.3	7.7	5.8	3.3	1.3	0.5	
Ohio, Columbus	0.6	0.8	1.1	2.3	3.5	4.6	5.6	5.1	4.1	3.0	1.6	0.6	
Okla., Oklahoma City	1.5	1.9	3.1	4.7	5.5	7.8	10.2	10.7	8.8	6.3	3.5	2.0	
Ore., Baker	0.5	0.7	1.4	2.5	3.4	4.4	6.9	7.3	4.9	2.9	1.5	0.6	
S.C., Columbia	1.6	2.4	3.2	4.5	5.4	6.3	6.6	6.0	5.5	4.4	3.0	1.9	
Tenn., Nashville	0.9	1.3	1.9	3.3	4.1	5.1	5.8	5.4	4.9	3.7	2.1	1.1	
Tex., Galveston	0.9	1.3	1.6	2.6	4.1	5.6	6.2	6.1	5.7	4.6	2.7	1.3	
Tex., San Antonio	2.2	3.1	4.5	5.6	6.5	8.4	9.4	9.4	7.6	5.8	3.7	2.4	
Utah, Salt Lake City	0.8	1.0	2.0	3.5	5.1	7.9	10.6	10.4	7.3	3.9	2.0	1.0	
Va., Richmond	1.3	1.7	2.2	3.5	4.1	5.0	5.6	4.9	4.1	3.2	2.4	1.5	
Wash., Seattle	0.8	0.8	1.4	2.1	2.7	3.4	3.9	3.4	2.6	1.6	1.1	0.7	
Wis., Milwaukee	0.6	0.7	0.9	1.3	2.1	3.2	5.0	5.4	4.7	3.2	1.6	0.6	
Gulf off Texas Coast	4.0	4.0	3.5	3.5	4.0	4.5	5.0	5.5	6.5	6.5	6.0	5.0	
Gulf Stream off Cape Hatteras, N.C.	9.0	9.5	8.5	7.0	5.5	3.5	3.5	3.5	5.5	9.0	9.5	10.0	
Ocean off Massachusetts	3.0	2.5	2.0	1.5	1.0	1.5	1.5	2.0	2.5	3.0	3.5	4.0	

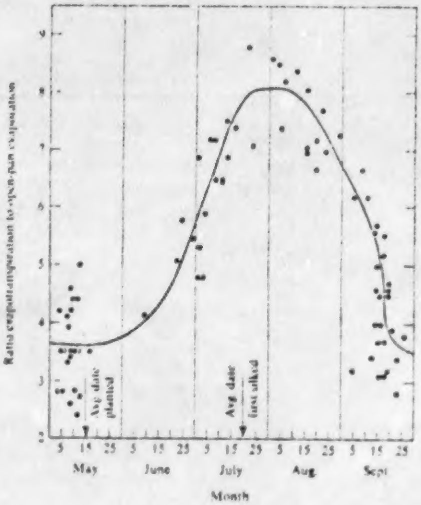
TABLE 2. ESTIMATED EVAPOTRANSPIRATION FOR TYPES OF VEGETATION IN THE WESTERN UNITED STATES

(Source: Select Committee on National Water Resources, U.S. Senate, 1960)

(from The Water Encyclopedia, 1970,
D. K. Todd, Editor)

Vegetation type	Annual Evapotranspiration, inches
Forest:	
Lodgepole pine	19
Engelmann spruce-fir	15
White pine-larch-fir	22
Mixed conifer	22
True fir	24
Aspen	23
Pacific Douglas-fir-hemlock-redwood	30
Interior ponderosa pine	17
Interior Douglas-fir	21
Chaparral and woodland:	
Southern California chaparral	20
California woodland-grass	18
Arizona chaparral	17.5
Piñon-juniper	14.5
Semiarid grass and shrub	10.6
Alpine	20

Figure 9 The ratio of evapotranspiration from corn to open-pan evaporation as a function of time during the growing season. (From Dunne and Leopold, 1978).



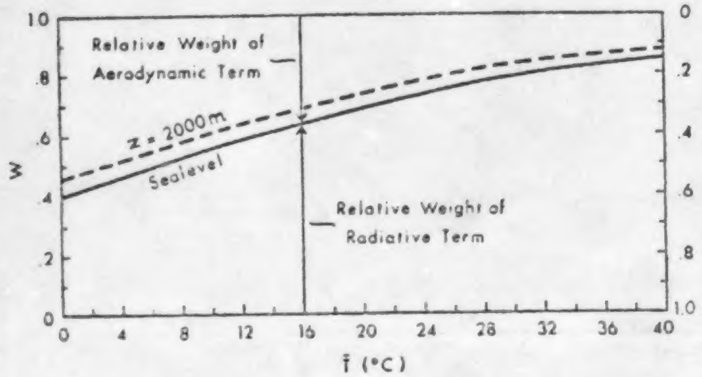


Figure 10 The dependence of weighting terms (w, 1-w) on temperature and pressure.

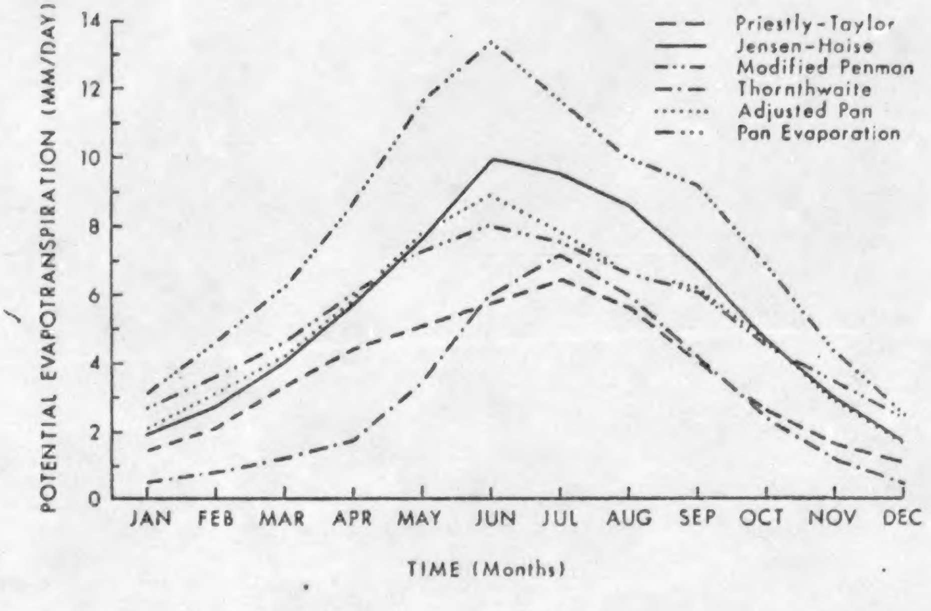


Figure 11 Estimates of potential evapotranspiration by several methods at Tucson, Arizona, for the period 1966 - 1975. The methods are described in the text.

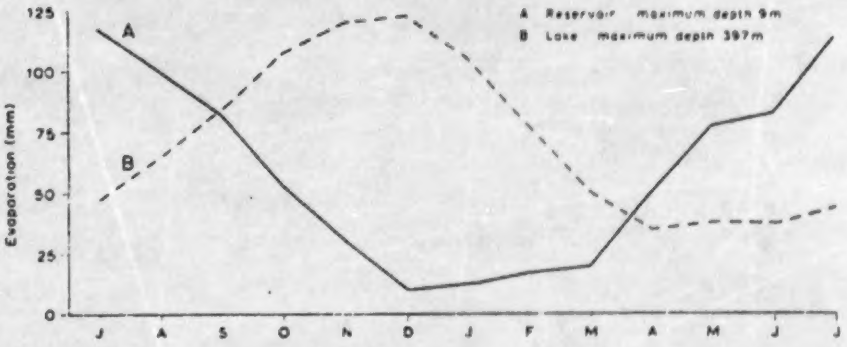


Figure 1. Graphs showing the trend of evaporation through the year from (A) Kempton Park Reservoir, London and (B) Lake Superior (from Ward, 1975).

Table 5

Table of evaporation from Pyramid and Winnemucca Lakes, Nevada (Hounam, 1973).

Period	Evaporation in millimetres	
	Pyramid Lake depth 61.0 m	Winnemucca Lake depth 4.6 m
March to August	573	924
September to February	652	290
Total for year	1 224	1 213

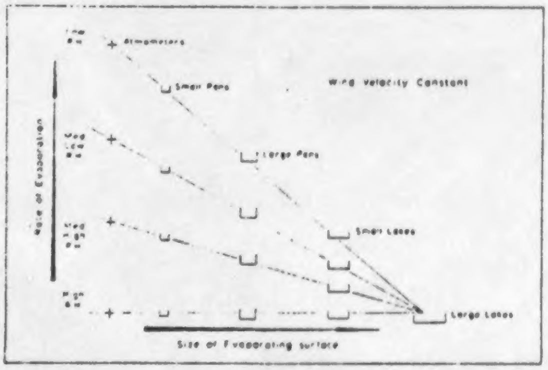

Low RH
Atmometers
Small Pans
Wind Velocity Constant
Rate of Evaporation
Med Low RH
Large Pans
Med High RH
Small Lakes
High RH
Large Lakes
Size of Evaporating surface

Figure 2. Diagram to indicate the relationship between the rate of evaporation and the size of the evaporating surface and the relative humidity. (From an original diagram by C. W. Thornthwaite and J. R. Mather, published in Climat., 8:1-86, 1955, Ward, 1975).

Table 9

Energy Budget Components at Bernardo (Gay and Fritschen, 1979)

	Q_1^*	G	LE_1	H_1	$K\downarrow$	Q_2^*	G	LE_2	H_2
June 14, 1977	451	−33	−518	100	730	461	−33	−450	22
June 15, 1977	486	−29	−554	127	736	464	−29	−435	0
June 16, 1977	452	−30	−498	75	765	470	−30	−429	−11
June 17, 1977	439	−30	−493	84	738	452	−30	−429	7
June 18, 1977	439	−38	−502	91	690	443	−28	−424	9

Daily totals in calories per square centimeter per 24 hours.

Table 10

Evapotranspiration Totals at Bernardo.

	LE_1	LE_2	lys_3	lys_4	lys_5	lys_6
June 14, 1977	8.8	7.7	6.4	6.5	8.8	9.0
June 15, 1977	9.5	7.4	6.5	6.9	9.3	9.1
June 16, 1977	9.5	7.4	6.2	6.5	9.0	9.0
June 17, 1977	8.4	7.3	6.6	6.8	9.2	9.3
June 18, 1977	8.6	7.2	6.2	6.8	9.4	9.4
Mean	9.0	7.4	6.4	6.7	9.2	9.2
Means	8.2		7.9			

In millimeters per 24 hours.

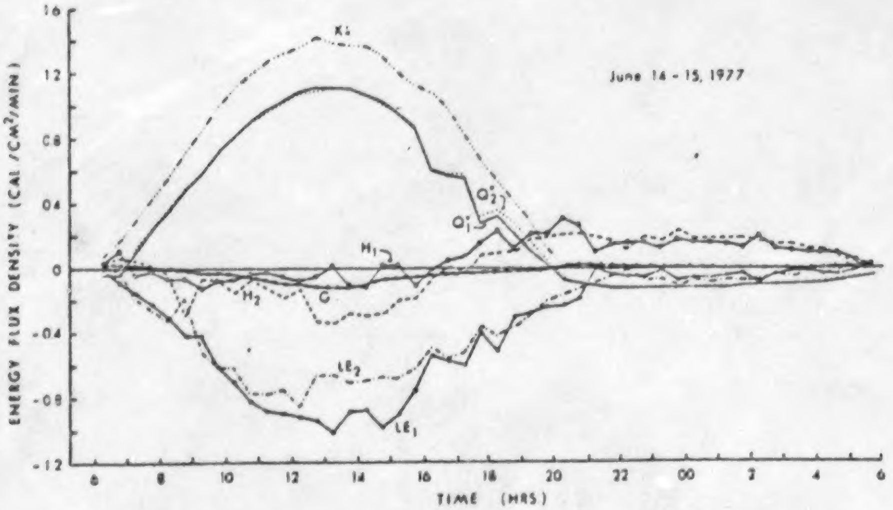


Figure 13 Energy transfer rates over saltcedar at two sites near Bernardo, N.M., June 14–15, 1977. The time axis is Mountain Daylight Time (MDT). Symbols are K *, solar radiation; Q*, net radiation; G, soil heat flux; H, convection; and LE, latent energy. Subscript $_1$ is the site with the taller, more vigorous vegetation. (Gay and Fritschen, 1979.)

Table 6

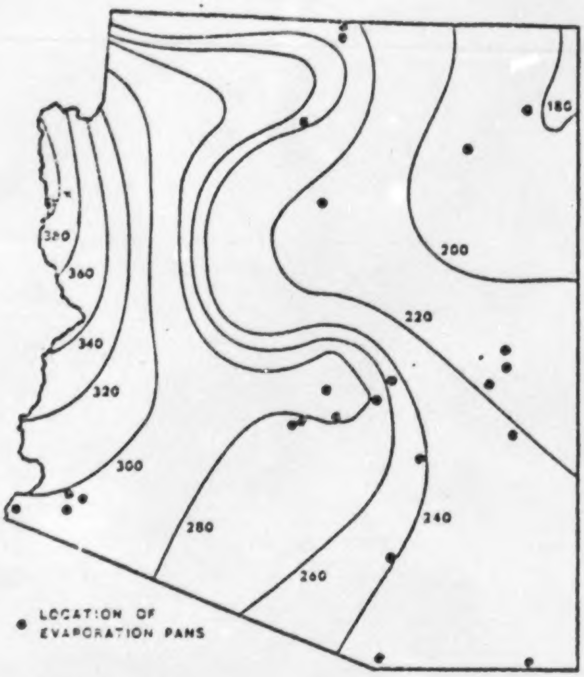
Evaporation pans in use in national weather networks (Hounam, 1973).

	area (m^2)
Colorado sunken pan, 3 ft^2, 18 in deep (USA	0.84
CGI 20 dia. 5 m, depth 2 m (USSR)	20
Sunken pan, dia. 12 ft, depth 3.3 ft (Israel)	10.5
Symmons pan 6 ft^2, depth 2 ft (UK)	3.3
BPI dia. 6ft, depth 2 ft (USA)	2.6
Kenya pan dia. 4 ft, depth 14 in	1.2
Australian pan, dia. 3 ft, depth 3 ft	0.7
Aslyng pan, 0.33 m^2, depth 1 m (Denmark)	0.3
CGI 3000 dia. 61.8 cm, depth 60-80 cm	0.3
Sunken pan dia. 50 cm, depth 25 cm (Netherlands)	0.2

Table 7

Annual coefficients for lake to Class A pan evaporation (E_L/E_P) (Hounam, 1973).

Location		Surface area in square kilometres	Average depth in metres	Pan coefficient	Observation period	Control method	Reference
Lake Elsinore	California	22.27	3.05	0.77	1939-41	Water budget	Young (1947)
Red Bluff Resv.	Texas	-	-	0.68	1939-47	Water budget	Kohler (1954)
Lake Okeechobee	Florida	1813.0	3.05	0.81	1940-46	Water budget	Kohler (1954)
Lake Hefner	Oklahoma	9.82	7.93	0.69	1950-51	Water budget	Sellers (1965)
Felt Lake	California	0.26	6.40	0.77	1955	Water budget	Kohler (1958)
Lake Colorado City	Texas	6.29	4.88	0.72	1954-55	Energy budget	Kohler (1959)
Lake Mead	Arizona	512.87	53.68	0.60	1952-53	Energy budget	Kohler (1958)
Lake Mendota	Wisconsin	39.11	12.20	0.81	27 years	Energy budget	Sellers (1965)
Salton Sea	California	777.01	7.32	0.52	1961-62		Sellers (1965)
Silver Lake	California	51.80	0.91	0.61	1938-39	Water budget	Kohler (1954)
Fort McIntosh	Texas	-	-	0.79	1950-51		Kohler (1958)
Kempton Park	London	0.16	7.01	0.79	1956-62	Water budget	Lapworth (1965)
Lake Eucumbene	N.S.W.	93.16	23.77	0.86	1962-64	Bulk aerodynamic	Snowy Mountains Hydro-elec. Authority (unpublished)



AVERAGE ANNUAL PAN EVAPORATION
(Centimeters)

Figure 6 Average annual pan evaporation in Arizona (adapted from U.S. Dept. Comm. 1968).

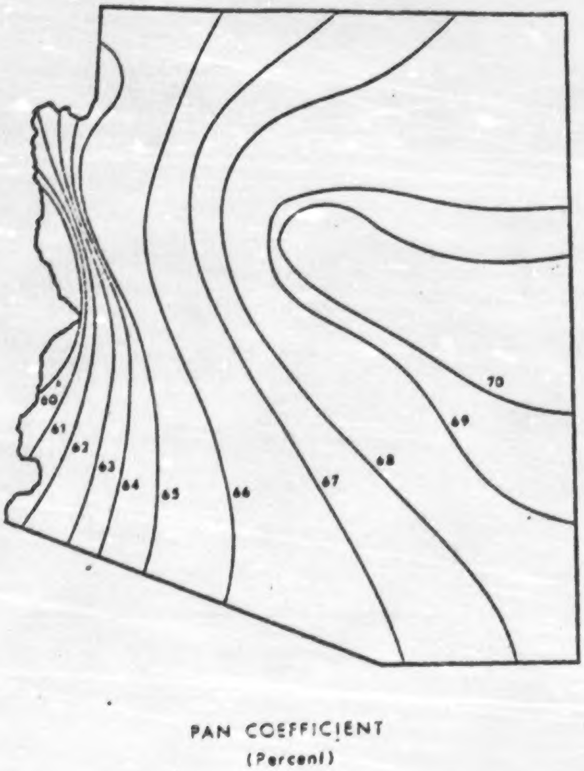
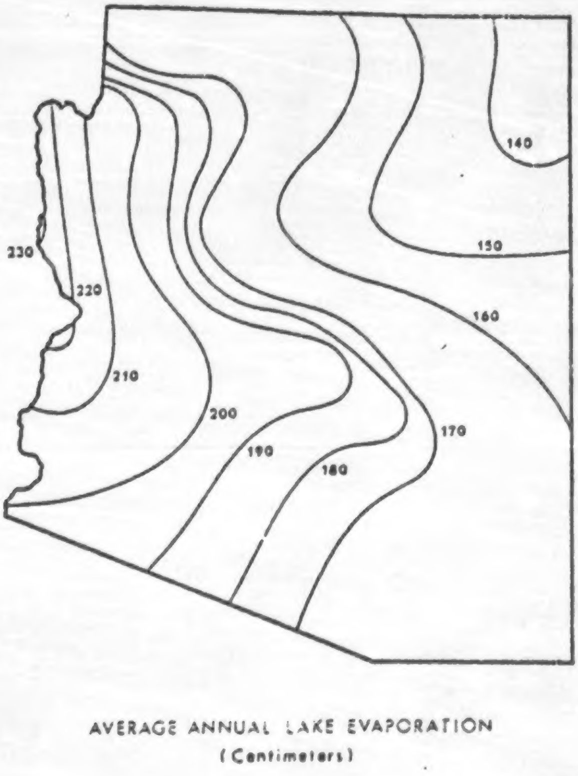
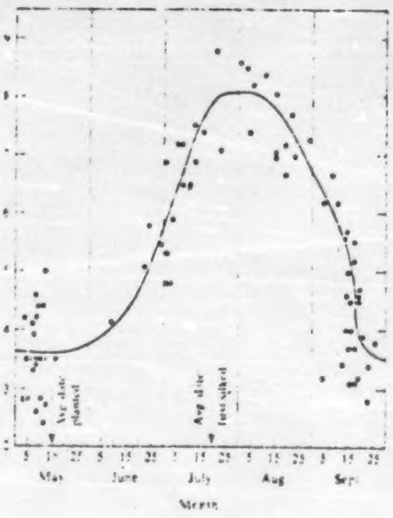

60
61
62
63
64
65
66
67
68
69
70
PAN COEFFICIENT
(Percent)

Figure 7 Coefficients to adjust evaporation pan measurements for micro-climate variations (U.S.

Figure 8 Annual lake evaporation in Arizona (adapted from U.S. Dept. Commerce, 1968)


140
150
160
170
180
190
200
210
220
230
AVERAGE ANNUAL LAKE EVAPORATION
(Centimeters)



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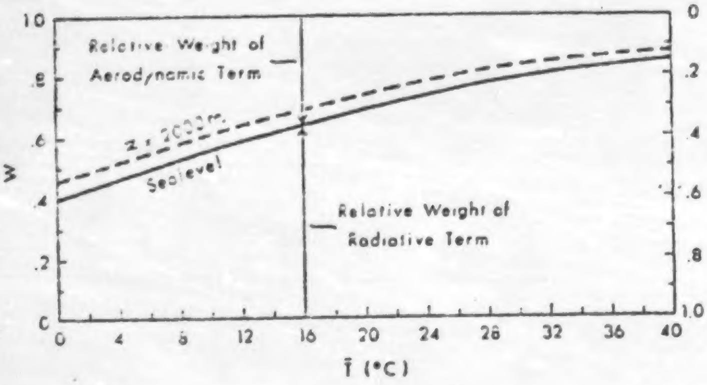

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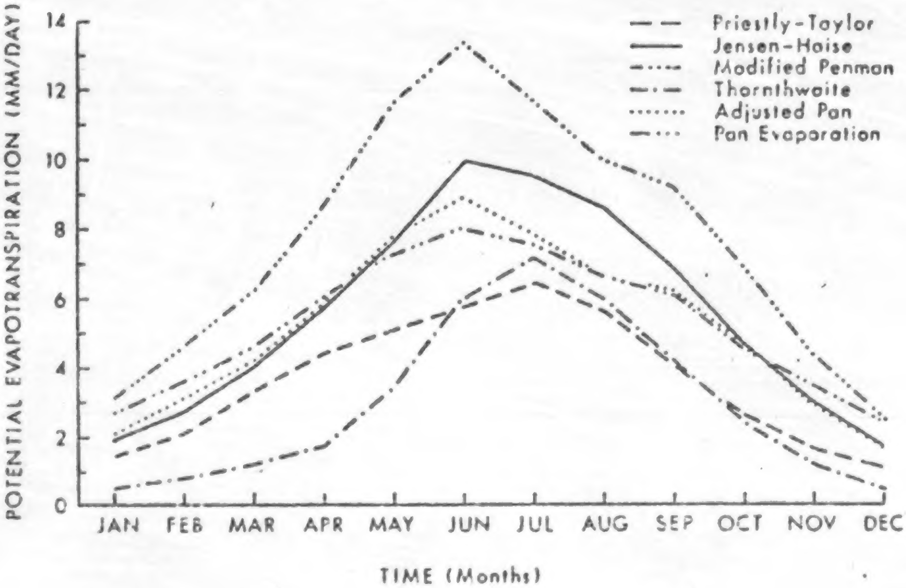

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Table 8

Mean evaporation at Tucson, Arizona (1966 - 1975). Amounts are totals (cm/month, or cm/year).

Method	J	F	M	A	M	J	J	A	S	O	N	D	Total
Evap. pan	9.5	12.9	19.1	25.9	36.0	40.0	35.9	30.7	27.6	21.0	12.9	7.3	273.4
Adjusted pan	6.4	8.6	12.8	17.4	24.1	26.8	24.1	20.6	18.5	14.1	8.6	5.3	187.3
Jensen	5.9	7.6	12.4	17.1	23.6	29.7	29.5	26.7	20.4	14.3	6.7	5.3	201.2
Penman	8.4	10.1	14.3	18.3	22.6	24.0	23.3	20.5	18.3	14.0	10.5	7.4	191.7
Priestly	4.2	6.0	10.0	13.1	15.7	17.1	19.9	17.4	12.0	8.9	4.9	3.5	132.7
Thornthwaite	1.6	2.2	3.7	5.1	10.5	18.0	22.0	18.6	12.6	7.4	3.6	1.6	106.3

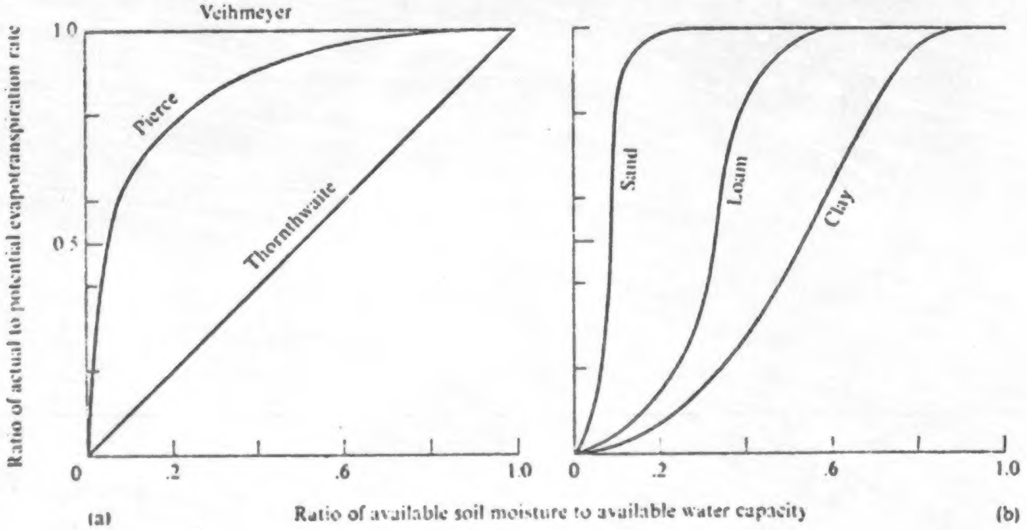

Figure 12 Relation of actual evapotranspiration to available soil moisture. (a) Actual evapotranspiration as a ratio to potential plotted against the ratio of available soil moisture to available water capacity according to models of three investigators. (After Holmes and Robertson, 1959.) (b) Ratio of actual to potential evapotranspiration as a function of soil moisture for three soil textures. The ratio of available soil moisture to the available water capacity varies from 0 at the permanent wilting point to 1.0 at fiele capacity. (After Holmes, 1961.) (From Dunne and Leopold, 1978.)

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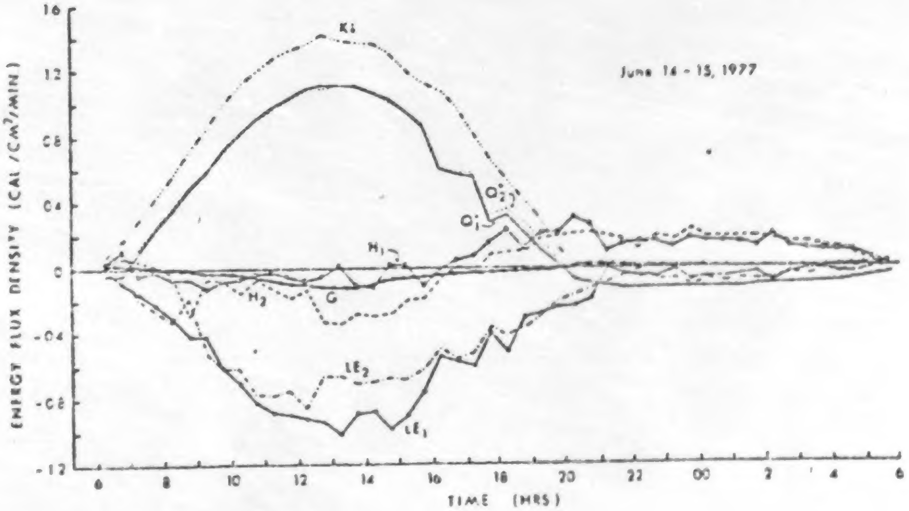
June 17, 1977	8.4	7.3	6.6	6.8	9.2	9.3
June 18, 1977	8.6	7.2	6.2	6.8	9.4	9.4
Mean	9.0	7.4	6.4	6.7	9.2	9.2
Means	8.2			7.9		

In millimeters per 24 hours



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